PB-239 117

ANALYSIS MODELS FOR SOLID WASTE COLLECTION

VOLUME I

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

PREPARED FOR
NATIONAL ENVIRONMENTAL RESEARCH CENTER

JANUARY 1975

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TECHNICAL REPORT DATA

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1. REPORT NO.
EPA-670/2-75-026a

2.

3. PB 239 117

4. TITLE AND SUBTITLE
Analysis Models for Solid Waste Collection
Volume I

5. REPORT DATE
January 1975-Issuing Date

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
James F. Hudson
Donald S. Grossman
David H. Marks

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Department of Civil Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

10. PROGRAM ELEMENT NO.
1DB314; ROAP 02AAE; Task 03

11. XXXXXXXX/GRANT NO.
801633

12. SPONSORING AGENCY NAME AND ADDRESS
National Environmental Research Center
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

13. TYPE OF REPORT AND PERIOD COVERED

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
See also "Analysis Models for Solid Waste Collection, Volume II," EPA-670/2-75-026b.

16. ABSTRACT

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All models are designed as management tools for public collection from residences and include discussion of appropriate extensions to commercial and industrial collection and haul.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Collection Management Computers Refuse Routes	Solid waste Models routing Solid waste management Analytical models Linear program	13B

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US Department of Commerce
Springfield, VA. 22151

18. DISTRIBUTION STATEMENT
Release to Public

19. SECURITY CLASS (This Report)
Unclassified

20. SECURITY CLASS (This page)
Unclassified

21. NO. OF PAGES
230

22. PRICE
7.50

PRICES SUBJECT TO CHANGE

EPA Form 2220-1 (9-73)

037021

EPA-670/2-75-026a
January 1975

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Volume I

By

James F. Hudson
Donald S. Grossman
David H. Marks
Department of Civil Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Grant No. 810633
Program Element No. 1DB314

Project Officer

Donald A. Oberacker
Solid and Hazardous Waste Research Laboratory
National Environmental Research Center
Cincinnati, Ohio 45268

NATIONAL ENVIRONMENTAL RESEARCH CENTER
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

In this report, analytic models are developed as aids in decision-making at many points in the solid waste collection and haul system. All models are designed as management tools for public collection from residences and include discussion of appropriate extensions to commercial and industrial collection and haul.

A. W. Breidenbach, Ph.D.
Director
National Environmental
Research Center, Cincinnati

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This report describes the research under the environmental Protection Agency Contract, "Analysis Models for Solid Waste Collection"(801633). Analytic models are developed as aids in decision-making at many points in the solid waste collection and haul system. Models for daily operating policy include breakdown or excess load, maintenance and stochastic influences such as weather. Longer range issues include choosing a level of service and the implications upon equipment, crew size, and work rules of such a decision. The primary thrust of the report develops an econometric model for prediction of waste output from census data and then districts into daily collection areas. A computer based districting methodology is outlined; an easily applicable heuristic for routing trucks within the districts was also developed. Actual data from Brookline, Massachusetts, serves in a sample application of the proposed models. Finally, on the regional level, a Linear Programming Model for equitable and efficient system design has been realized.

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ACKNOWLEDGEMENTS

This work was supported financially by the Solid Waste Research Laboratory, U.S. Environmental Protection Agency under grant number 801633. Administrative support was provided by the M.I.T. Department of Sponsored Research under DSR numbers 73421 and 80572.

The work was performed by Dr. David H. Marks, Principal Investigator and Associate Professor of Civil Engineering, and James F. Hudson, Donald S. Grossman and Louis A. Fuertes, Research Assistants in Civil Engineering Systems. The authors of this final report would like to express their thanks to Mr. Fuertes for his work during the first year of the research, primarily on the Regional Processing, Haul and Disposal model.

The authors gratefully acknowledge the assistance in data gathering provided by various individuals in the Brookline Department of Public Works, the Raytheon Service Company, UNITEL, and Boeing Computer Services. We would also like to thank Chris Ungate, Herman Kwai, and B.A.A.N. Akonteh for their assistance in the research.

Special thanks are reserved for Pat Dixon and Erika Babcock for their patience and skill in preparing the report, and for Donald Oberacker, the EPA project officer involved in supervising the research.

INTRODUCTION

This is the first of two volumes in the final report for the contract "Analysis Models for solid Waste Collection" sponsored by the U.S. Environmental Protection Agency (Contract 801633, M.I.T. Division of Sponsored Research Nos. 73421 and 80572). The primary goal of the project was to investigate the application of mathematical modelling and systems analysis to the problems of local and regional solid waste management, and to attempt to develop tools to aid in the decisions made in such systems. The work was therefore structured in terms of these decisions, as opposed to the type of model or the solution technique, and this report is similarly structured. The present chapter contains an overview of the decision classifications made and the models developed. Chapter 2 describes the types of operations of agencies who might use such models and their goals. In chapters 3-9 a detailed presentation is made of the work done in each of the decision areas, both under this contract and in other research. Chapter 10 summarizes the work, and suggests methods for increasing the use of innovation in solid waste collection systems and productive areas for future research.

In volume 2, the models developed are described in detail, and listings are given of the various computer routines constructed in implementing them. These routines are written primarily in FORTRAN and MPSX, to insure transferability to most installations.

1.1 Decision Classifications

There are several ways to structure the decisions made in the solid waste management process. One possibility would be by decision-maker: thus, the driver might choose his route, the system manager decide on crew tasks and the number of men and trucks to be used, the local government might choose collection frequency, and the county government investigate and develop disposal sites. However, this is unrealistic since many of these decisions are made by multiple decision-makers at various levels. Everyone has an input into the process, and most decisions are made by consultation between several impacted people or groups, either explicitly or implicitly. This is increasingly true as the scale of the decision grows: a few residents may be affected by routes where too many vehicles pass their homes and may complain, but this is a small effect compared to the negotiations required in the development of a landfill site.

A better method is to look at the time span of the decision and attempt to develop aides for the decision-makers which are of value at each level (see figure 1.1). Short term operating decisions are the lowest level. Examples would be overtime policies , contingency plans for handling breakdowns, holidays, or heavy loads; routing of bulk pickup vehicles where the requests come in randomly, and similar issues. Such decisions are usually made by the system manager who is concerned with minimizing the cost of providing a given level of service and constrained by his resources in men and equipment and fixed policies such as the work rules. The decisions are operations management, and the service provided to the public is set at a fixed level.

The second level of decision making is also concerned with operations, but over a longer time span. While operations decisions are made daily, the intermediate range options are usually considered a few times a year at most, and often only every few years. Vacation scheduling might have the shortest lifespan, with assignments made perhaps as often as monthly. Equipment selection would be near the upper end, with several years between decisions. Vehicle routing, maintenance policies, and work rules are also sample problem areas in this category. These decisions are major choices for the system operators, and are areas where mathematical modelling and systems analytic techniques are applicable, at least if they can be applied in a low-cost manner.

There is a third set of operations decisions in solid waste which has an even longer time span: the construction and use of fixed facilities. Collection is done in small neighborhoods spread over the community; processing, transfer, and disposal occur at a few fixed points. Given a configuration of disposal sites, transfer stations, and processing plants, it is possible to allocate the vehicles for haul to the various sites in a least cost manner. The generalization of this problem involves not only allocation of haul, but also the siting and construction of the fixed facilities. Again, this problem can be solved reasonably well using mathematical analysis techniques, given an efficiency objective of minimizing total system cost. This, though, is not a reasonable objective for an actual system: facility location depends on a host of equity and environmental impact issues, not just on which solution would lead to lowest system direct cost. As described below (Chapter 9) attempts have been made to consider surrogates of these social variables in solving regional location-allocation problems, to give the decision makers an opportunity to investigate these effects of various configurations with respect to both the economic and social objectives.

In community collection systems, there are a number of decisions which involve changes in the service provided to the residents. In one respect, the yearly budgetary process is such a decision,

Short Term

- Intuition
- Rules of Thumb
- Heuristics

Medium Term

- Rules of Thumb
- Experimentation
- Heuristics
- Simple Analytic

Long Term

- Analytical

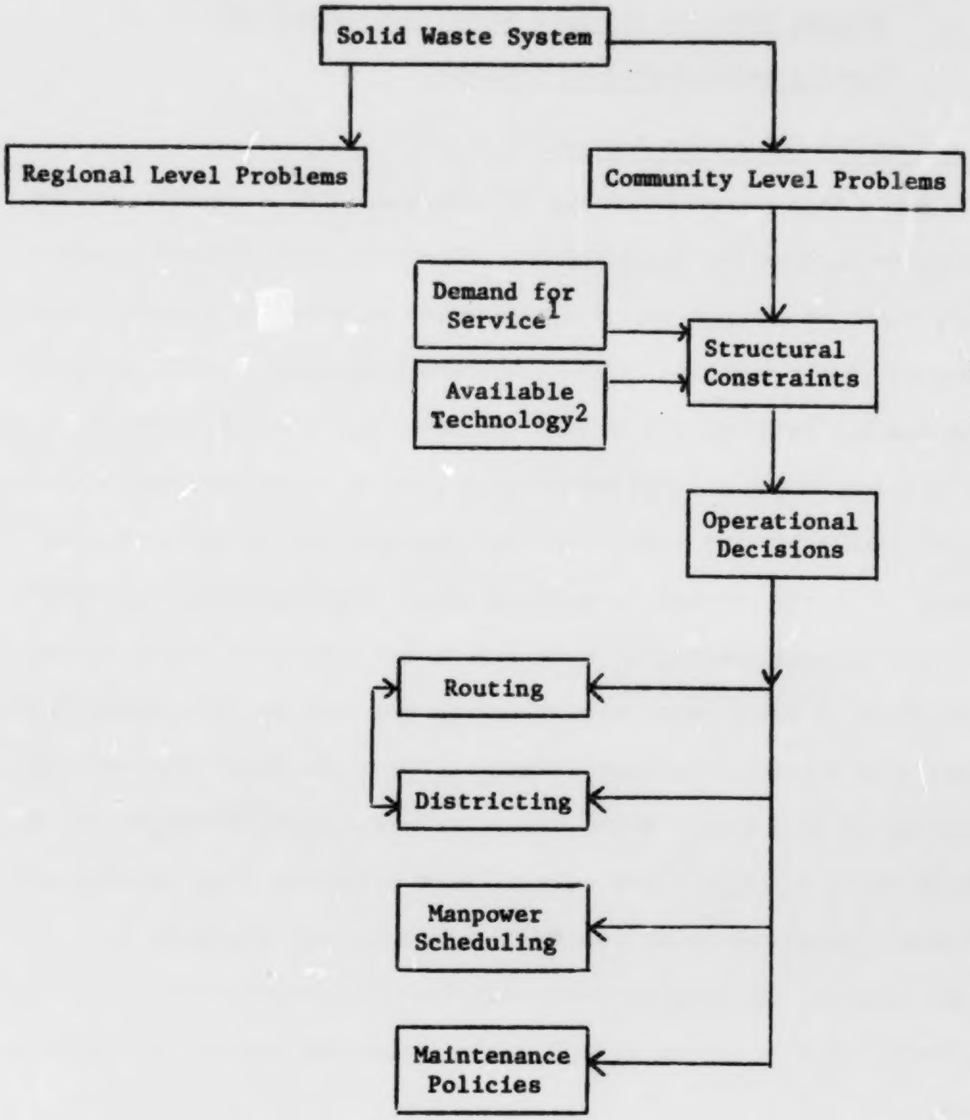
Figure 1.1: Decision Making Aids

so that efficiency is closely related to level of service through financing or taxes. The level of service also includes variables such as frequency of collection, type of storage system, noise, odors, traffic, litter, place of pickup, and a number of other aspects. The interaction between system cost and the public sanitation and environmental requirements is complex and difficult to estimate. Even in the simplest cases, for example an increase in the truck size used, it is not easy to estimate the possible cost savings or the new impacts on the residents from factors such as changes in traffic or time of pickup. When a major change is made such as increasing the frequency of collection, this becomes much harder, even if most factors are held constant. When the really interesting options are investigated such as a change in frequency of collection combined with some new equipment and new routes for the vehicles, an accurate assessment of the various impacts is nearly impossible given the present state of the art. Large simulation models have been built to look at such issues, but are very expensive to operate. Smaller, more manageable models are only accurate for a limited range of decisions.

1.2 Research Under the Contract

For several reasons, the present work has been concerned primarily with operations issues. First, such problems are the best defined and can therefore be most readily attacked with available tools. Second, there was a reasonable *a priori* probability of success in developing methods which would be of use in actual collection systems. Finally, the costs of collection are so large that any operational changes might have significant impacts on the level of service a community could afford to provide, while a lack of improved operations methods combined with increasing costs might lead to a reduction of service below acceptable sanitation standards. In other words, it was felt that improving the understanding of the effects of changes in the service provided would be of little use compared to improving the methods for providing an already acceptable level of service at a lower cost.

Figure 1.2 shows the relationship between the models developed in this research and a general overview of the solid waste system. As can easily be seen, the majority of the models are intermediate range operational decision aids. Such decisions are very important in community collection systems, since they essentially determine many of the system costs and many of the productivity variables. A good example would be the choice of crew size or of equipment. Once one of these decisions is made, the range of choices available in the other is greatly restricted. The daily operational policies are even more restricted, of course, but the feedback between such policies and the longer term decisions is slight.


Solid Waste System
Regional Level Problems
Community Level Problems
Demand for Service[1]
Available Technology[2]
Structural Constraints
Operational Decisions
Routing
Districting
Manpower Scheduling
Maintenance Policies

[1] Depends primarily on frequency of collection, place of collection, amount of waste generated, topography and demography.

[2] Depends primarily on number of vehicles and sizes and types, crew size, number of fixed and disposable containers, state-of-the-art in new equipment, and tradition.

Figure 1.2: General System Overview

The models developed here include a set of routines for districting a community into tasks requiring an average of one truck day each and for routing the trucks within these districts. As a basis for this districting, a predictive model for the amount of waste generated in a block and the time required to collect it has been developed using census block data as a base. A method for aggregating the crew tasks into daily collection areas and weekly truck routes has also been designed. The districting routine requires a moderately large computer installation (400K bytes for the Brookline problem) and the waste generation and time requirement models require access to the Census block tapes (third count), or at least to the published versions if a population-based model is used. Routing is a simple matter after districts are designed, and heuristic techniques for nearly optimal manual route design are described below (Chapter 6).

A secondary routing problem is that of collecting from fixed points, such as dumpster boxes (or, alternatively, from random fixed points such as bulk collection service). A version of the Clarke and Wright Truck Dispatching heuristic was programmed and has been used for an example problem of this type. An investigation was also made into policies for allocating vehicles where a random probability of breakdowns or overloads existed, and trucks could be dispatched to assist on routes where these random events occurred. This was done in an attempt to develop rules of thumb for the number of extra vehicles which should be available. These community level models are described in chapters 4-8 along with similar research by others.

The short and long-term operations problems are described in chapters 3 and 9 respectively. Chapter 9 considers the facility location-allocation problem under a multiple objective system (e.g. minimize both cost and environmental impact of the processing, haul, and disposal system). Chapter 3 looks at the possibility of using low-cost analysis aids in the daily operation of a collection system, such as Bayesian techniques for the prediction of wasteloads depending on loads over the previous weeks. These techniques were not developed during the course of this research, but are one possible area for future work. Table 1.1 shows a list of problems for each of the general decision horizons, and which sections of this report refer to each problem.

Length for Decision	Decision Category	Reference
Short	Overtime	3.1
	Bulk Pickup	3.2
	Breakdown	3.3
	Overload	3.3
	Work Rules	3.6
	Routing	6.5, 6.6
Medium	System Configuration	2.7, 3.8, 8.1
	Equipment Choice	4.3
	Crew Size	4.3
	Level of Service	4.1, 8.1
	Vacation Scheduling	4.2
	Maintenance	3.4
	Routing	6.5, 6.6
	Districting	5.1
Long	Haul	9.1,9.3
	Transfer	9.1,9.2
	Processing	9.2,9.3
	Disposal	9.2

Table 1.1: Decision Classifications and References

WHO WILL USE THE MODELS

In any modelling effort, it is vital not only to look at the technical issues involved, but also at who will use the models after they are developed. There are many important actors in solid waste systems, from the operators of both public and private collection systems, to the crews, residents, and businesses and the coordinating agencies such as EPA. We have based our work around public residential collection, although many of the methods developed by us and by others could be applied in private systems. This chapter will attempt to briefly describe the various actors, their goals, and the constraints upon their operation.

2.1 U.S. Environmental Protection Agency

It seems fitting to start with the U.S. Environmental Protection Agency, since they have provided support for this and other modelling research. EPA was formed in 1971 and is charged with "the development of improved methods of solid waste management", among other things. They have provided most of the support for solid waste research, both towards improving environmental impacts and towards increasing efficiency and lowering costs. These are fairly simple goals; the problem is the methods used for making them operational. Money for promoting innovation in collection systems is not available, except for basic demonstration projects. It may be possible in the future for EPA to provide some sort of technical assistance on a wide scale, perhaps distributing handbooks or computer packages and providing the supporting staff for such materials. They will not be applying the models themselves, but may provide information and support services.

2.2 Other National Organizations

There are a number of other organizations concerned with solid waste at the national level. A few include:

1. The National Solid Waste Management Association
2. The American Public Works Association (especially the Institute of Solid Wastes)
3. The National Center for Resource Recovery
4. The National Association of Counties

Again, these agencies are not concerned with direct implementation or use of models, but may provide a base for change. They are usually made up of the more innovative sectors of the system, and are concerned with efficiency of operations and promoting change where desirable. They cannot go into systems and directly support change (except in a few special cases), but may also be able to give technical support to system operators.

2.3 Consulting Engineering Firms and Universities

Many of the large scale problems in solid waste management require comprehensive and detailed analysis, beyond the ability of the technical staff in all but the largest collection systems (for reasons of manpower, if not of skill). The regional processing, haul, and disposal models are good examples. The use of such models, and the investigation of such problems, requires skilled personnel such as those found in consulting engineering firms or universities. The time span on university research, though, is long; actual implementable results are more likely to accrue through the use of consultants. If large models are to be useful in the real world, they must be usable by these consultants. This suggests that the models must give good results for real problems, and require only data which can be collected at acceptable cost. They also must not be prohibitively expensive to run. The model must also be easily understandable both to the consultants and their clients--a "black box" giving great results will not be trusted. Sensitivity analysis capabilities are important, so that various plans can be tested against each other and against experience, instead of a single "optimal" plan being generated.

2.4 State Solid Waste Agencies

State organizations are in much the same position as EPA: charged to faster change under severe budgetary constraints. They are primarily concerned with disposal systems, and usually attempt to promote regionalization. Any models used will be important as "theater"--more for showing the value of regionalization or improved disposal methods than for actual design purposes. Gaming techniques, and regional models with sophisticated output and sensitivity analysis capabilities are important here. It is crucial to show the impacts of "hands-on" changes in the system on cost and on the environmental indicators. Major design studies may be important, but are not likely to convince people. Models for use in this context differ significantly from those used elsewhere. They should be tools for quick analysis of different configurations as an aid in negotiation, and need not be concerned with detailed design. Chapter 9 shows such a model, and some simple examples of its use.

2.5 Regional Disposal Agencies and Counties

We are assuming that the major users of regional operations models will be special agencies and counties, and that collection will take place at the community level of jurisdiction. Such regional agencies will be able to use the regional optimization models in a manner similar to the states -- as tools for convincing people that regional systems are valuable -- and also for testing a large number of alternatives at a basic level. Their goals are to produce a system which will be efficient and acceptable to the residents and operating collection agencies. This probably requires both models for preliminary screening of alternatives and other models for detailed testing of designs. Since most agencies of this type do their modelling when being set up, there is no real tendency to just continue the status quo: if the situation is bad enough to require regionalization, everyone realizes that changes are necessary, and that careful design must be done. Note that some states are taking over this role of coordinator of disposal systems (91), while others have enabled their counties to run such systems (19).

2.6 Private Collection Operations

Most private collection systems service commercial and industrial loads often using containerization. They are very concerned with efficiency, since the market tends to be extremely competitive This objective is important for private residential collection, either through public contract or individual private collection. While the service provided is important, it is usually the cost of providing it which is considered paramount. Thus, private cartage firms are more likely to adopt improvements in operations methods than the more service-oriented public collection organizations. In fact, the larger companies (for example, Sanitas and Industrial Services of America) are major innovators in equipment and methods for management in the field. Private operation allows some economies of scale, since equipment can be moved around to meet demands as necessary. It has been suggested that New York city should allow private haulers to compete in some collection tasks and geographical areas with the Department of Sanitation, to improve service and efficiency (92,113). While we will not support this view, there are clear advantages in private systems for efficiency, if significant competition exist. The problems arise with externalities: private companies will provide the service desired by the user, and the externalities upon other residents are often not considered important. In small companies with only a few trucks, models are not likely to be useful. Route design can be done by the operator just as well as the analyst. In the largest systems, innovation has and will continue to occur. Some companies have set up internal consulting groups or subsidiaries for technical analysis.

2.7 Public Collection Operations

There are some reasons for running collection as a municipal service, and giving that service a monopoly over some classes of customers (especially residential collection). First, an acceptable level of service is provided for all, so that public health and sanitation standards are met without large enforcement requirements. Second, areawide monopolies reduce significantly the number of trucks required, and can lead to cost savings (33). Finally, solid waste collection can be considered to be a utility which should be available to all residents. However, public systems tend to be resistant to change. One important effect here is the feedback from the residents. Any failure in solid waste service will get loud and vocal response from the community. Preservation of service at least at the status quo is very important. On the other hand, solid waste is a small portion of the total municipal budget, and past cost increases have often received a much weaker response. Thus, there has been a strong incentive to keep level of service constant and a much weaker one to minimize costs. The result is an acceptance that the present service is "best", and less-than-total concern about costs except when the situation becomes crucial. When that happens, major steps are taken and changes may result. Often the crews are resistant to change, and seem to almost have "veto" power. Municipal unions seem more effective than private, at least in solid waste systems: the threat of removing collection service is very strong, politically. The concern for service can lead to overdesign of the system; to being prepared for any contingency whether or not this preparedness can be justified financially. Municipal systems also tend to be tightly constrained on capital budgets, leading to use of larger crews and older equipment than in private systems.

These issues show some of the weaknesses of municipal systems in producing significant change. The constraints are very strong, and change necessarily slow. Costs have been rising too fast, though, and landfill space is often unavailable, so change is being forced upon the systems. Many communities are adopting analytical methods and the time when a major redesign is required is approaching quickly for many others. Collection is important; it is extremely costly; and some change is necessary. The use of analytical methods and modelling offers one possible approach for evaluating such changes and designing the best choices. Note that models which are to be used by local collection agencies must be low cost. They must be inexpensive to use, not only with respect to dollar cost, but also limited in their requirements for computer time, data, manpower, and technical skill. All of these resources are limited in real systems, and the models must recognize this. It seems likely at this time that the service constraints are strongest, and that models should first be used to increase efficiency by suggesting better operating policies for maintaining the existing service level. It may later become possible to change the service offered to one which fits the needs of the community better. For actual use in public agencies, though, the models should be addressed to operational issues which are important to the system managers, and should be usable by those managers and their technical staff.

Public agencies are where the major problems exist partially because of past resistance to innovation. This means that modelling could be most valuable to them if implementation occurred, but that such implementation faces many barriers. We have attempted to guide our work towards producing useful tools, and have attempted in this work to put together the research into a usable form. Implementation is however, the most important task and the area where the emphasis should occur. While agencies like EPA cannot economically support implementation on a wide scale, promotion and technical assistance for the various methods developed here and elsewhere would be invaluable. Availibility of the models and techniques is clearly necessary.

2.8 Brookline, Massachusetts: A Case Study

Much of our work was performed using the town of Brookline, Massachusetts as a case study. Some data was available for estimating and validating our models, and the officials were fairly receptive to our work. A prototype for a case study seemed appropriate to bring the abstract down into real-world system operating terms. This report was written for both the analyst and the manager, for change cannot be expected unless the actual participants in the system accept and understand any proposed modifications. Analytic results should not be presented as coming from a black box, and here Brookline serves to light the box. A detailed discussion of the town's operation is to be found in Chapter 8. In the interim, it suffices to know that this report centers on weekly curbside residential pickup. As far as Brookline specifically enters, the existing level of service is 8 daily routes using 20 yard packers for roughly 60,000 residents total: special 10 yard packers called "Alley cats" service small streets inaccessable to the larger trucks. As much as possible, of course, the models were constructed to be independent of the particular system where the techniques are applied, but the basic models and the methodology should remain fairly constant.

MODELS FOR DAILY OPERATIONS POLICIES

The managers of solid waste collection systems have a wide range of decisions to make on a daily basis. Such decisions are usually made according to the dictates of past experience, a fixed set of operating policies, or intuition. Any models used to aid this process should be low cost, and should seek to supplement rather than replace the present policies.

Models could be used to design an improved set of operating policies, to increase the "feel" of the operators for the way the system works, or to suggest alternatives which might not otherwise have been found. In this manner the flexibility of operations could be increased by giving the decision-makers a wider choice of options. One good example is the work done by Altman, et al., in New York City (4). A major problem existed in assigning men and crews to the two-shift operation. There was a lack of good measures of demand combined with a strong set of constraints from the union on the relative use of first and second shifts. The analysis performed by the group developed a set of operating policies which would schedule crews to first and second shifts to meet the varying daily and weekly demands. These policies both decrease the costs of overtime operations and improve the working conditions of the crews. This is an example of an improvement in operating policies. At the regional level, the games developed by Wahi (133) and Klee (66) both attempt to increase the "feel" of system managers by dramatically illustrating the effects of changes in haul schemes and incinerator and landfill operations. A model developed by Stern (118) for processing plants shows the effects of different policies for inventory and loading: it could be used either to increase intuition or to assist in daily operations. The information systems developed in Toronto (7) and Wichita Falls (77) attempt to give the manager a tool for integrating data collected daily into useful information.

Many issues might arise on any particular day. For example, there could be a question of whether to give overtime to a few crews or to save the uncollected waste until the next morning: one costs money, the other community good will and sanitation. The weather has a significant effect on collection operations, and the haul distances vary over the course of the week. Breakdowns may occur, requiring reassignment of resources away from the basic long term policy; loads may be heavy in one area and light in another, leading to similar problems (especially where relay policies are used).

It is obviously not feasible to model every aspect of an operation and still come out with a model which would be usable and understandable. It may, though, be possible to model some areas and to suggest

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ideas about others which might otherwise be missed.

The remainder of this chapter looks at several areas in daily operations where either attempts have been made to apply analytical techniques or the operations seem especially favorable to such application.

3.1 Modelling of Overtime Policies

To a large extent, this section complements section 4.4, where the question of work rules is discussed. Here, though, the issues are slightly different. Instead of choosing the work rules, these basic rules are given and the problem is to use the available resources in some efficient manner.

Consider for example, a weekly route system with backyard collection. It is noon on Thursday, and the load for the week appears to be fairly heavy. Ten crews are operating, and six of them are behind schedule, in amounts ranging up to half a day. Overtime is given in units of one-and-one-half hours on weekdays, and four hours minimum for Saturday work. Note that this is not a pure weekly route system, since overtime is paid extra: this reflects the situation in some communities where increases in the amount of waste have not been met by similar increases in collection manpower. The result is extra work for the present crews and extra compensation for this work. The problem is to allocate the overtime so as to minimize the cost, and the decision depends on several factors. Of prime importance is the expected load on Friday, and the probability that the crews will finish their routes. These models could lead to estimates of the mean amount of overtime necessary and, perhaps, the variance. Thursday overtime, is probably not worthwhile, since it seems likely that the work cannot be completed on Friday with overtime, and the cost of using Saturday is not extreme. With some estimates of the probable amounts of waste left over Friday and the variance in this amount, a near optimal decision rule could be found.

The problem becomes more complex in a daily route (or incentive) system with an overtime structure. Important sanitation and esthetic issues arise from not collecting waste on the specified day. This is especially true if pickup is from curbside. A technique like decision analysis (see Raiffa (109) or deNeufville and Stafford (32)) could be used to analyze the "cost" of missed collections to the system manager in an attempt to develop policies which would minimize the total disutility of overtime and missed collections. This has not, to the best of our knowledge, yet been done. Tanaka (128) has developed overtime models which look at a generalized cost composed of overtime and missed collections for various policies. This is to some extent a mixing of apples and oranges, but the model could be used to develop a transformation curve between the two objectives of minimizing cost and minimizing missed collection (see, for example, Chapter 9 of this volume) for a reasonable comparison of the two goals.

As can be seen from this limited discussion, due to the limited state of the art in models of overtime policies, the tools developed would be at best aides in the decision-making process. Still, formalization of the rules used presently (as, for example, an estimate of the "cost" of missed collections) might be helpful. They would be especially useful for a neophyte manager, for they would give the newcomer a bit of "book-learning" which might reduce the errors made in acquiring real world experience. It can never be mentioned too often that models do not give perfect answers, but must be tempered by common sense and experience. This is especially true with highly abstracted models such as these.

3.2 Bulk Collection Systems

Bulk collections differ from ordinary solid waste operations in most communities, and in many ways closely resemble police or fire operations. In many systems service is requested by telephone, and demands are infrequent and spread throughout the community. A call comes in requesting pickup of, say, a couch and this is added to the queue to be served. The caller is interested in the response time until pickup; the manager wants to provide satisfactory service at low cost. This leads to the dynamic problem of routing the truck efficiently, considering the items to be picked up, the truck capacity, and the distribution of demands. In large areas, there is also a question of the number of bulk collection trucks to use. This depends in turn on truck productivity, the demand pattern, and the desired response time from receiving a call to pickup. The Clarke and Wright algorithm (28) is a simple alternative for the routing problem if done by hand:

- Mark the demand points on a map with their loads (e.g. in fractions of a truck load)

- Start joining points far away from the disposal site onto routes, choosing by maximum "savings"

- Do not join points which would bring routes over capacity

- When done, count the number of routes generated: assign the truck to these routes, and await further demands.

For the queueing problem and the decisions about the number of trucks and crews to use for the service, the models developed by Larson (71) may be useful. A single server with limited capacity receives calls during the day, and there is probably a high cost for not picking up a request received early in the day until the following morning. Larson's models give estimates of how much the addition of a second server (another truck) would be expected to improve the service provided. Another possible method of analysis would be a simple simulation: again, Larson gives an example for police problems of using a simulation method for allocating patrol cars to precincts depending on the demand pattern and other requirements such as a minimum level of response. The use of similar models might enable a system operator to quickly choose the "best" level of bulk collection service, depending on his desires, the funds available, and the needs of the service community. It is important to note, however, that these models require the use of cost analysis to complement the level of service estimates.

3.3 The Breakdown and Excess Load Model

In the course of the contract, we developed an expository model which looks at the problem of breakdowns and overloaded routes and at their combined effect on dispatching.

In the ideal waste collection system, all trucks receive demands for service equal to or below their possible productivity for the day, and no truck ever breaks down. Costs become easy to compute, with no real stochastic elements, and the fleet size is the minimum necessary to trade-off the cost of owning extra vehicles against the improved service provided by having these spare trucks available to respond to service delayed by breakdowns or overloaded routes. This model attempts to simulate a simple collection system to see the effects on level of service and operating costs of different numbers of vehicles. It is also possible to investigate the effects of changes in driver productivity, vehicle capacity, maintenance policies, and dispatching rules. The main use of the model, though, is to at least estimate the effectiveness of having different numbers of spare trucks available when something goes wrong in the operation.

Solid waste collection routes are usually fixed. In some cases relay policies enable underutilized crews to help on overloaded routes, but this is not common and requires very careful management. In this simple model, such relay policies are not considered.

Work has been done on choosing fleet size with consideration of the possibility of breakdowns; this is basically a queueing problem. Assume breakdowns are independent of the particular vehicle, and distributed as a Poisson process over the fleet. Queueing models yield the probability of having sufficient vehicles for a given fleet size given data on the mean time between breakdowns and the distribution of repair times. In solid waste systems, this has been applied by the Los Angeles County Sanitation Department in choosing the desired number of transfer vehicles (47).

No available models consider both the problem of random demand for service fluctuations and the random incidence of breakdowns as a unified whole. Obviously, it would be possible to purchase enough vehicles to do the routes under normal conditions plus spares for demand fluctuations plus spares for replacements if breakdowns occured. This, though, would be foolish: some savings should be available from jointly considering the two problems.

The simplicity of the model makes it much more of a screening tool than an actual vehicle for policy analysis, but it should be useful for at least getting a general idea of what the tradeoffs between reliable service and capital cost look like. In many ways, a screening model serves as a piece of theater -- used primarily to get the people in the real system thinking about these effects and attempting their own intuitive analysis. The model might be expanded, until it reproduced the real operation accurately: this would involve detailed modelling of the dispatching and communications strategies, and a great deal of data collection on the real collection system. At this point, expensive models cannot be justified: there is no real evidence that the problem addressed is a real one in a local system, and even less that modelling will provide any new information. The next stage in development should probably be to analyze the simulation more closely, and to see what critical factors have been ignored. It may then be possible to develop it into a useful (and usable) analytic tool.

Simulation as a technique, attempts to mimic system behavior under different conditions using a mathematical description of the real system. In a stochastic simulation, random numbers are used to generate unknown quantities on events which occur at unknown times, such as breakdowns. Simulation is an easy technique to use, since it is possible just to write equations describing the system and run them over a period of time, but it is expensive and limited -- especially in the number of alternatives which can be searched while looking for the optimal solution. The model was purposely designed to be as simple as possible, so that runs would be fairly inexpensive and many could be done in a fairly exhaustive search.

In the model, there are two separate processes: the vehicle process and the dispatcher. The vehicles are assumed identical, and travel on routes which require varying amounts of time. The dispatcher controls the use of these vehicles, assigning them to routes in the morning and using the spares to help if breakdowns or overloaded routes occur. That, in essence, is the model; to generate reasonably accurate statistics, it is run for many days so that the random events will be included into the operation.

It is necessary to make many heroic assumptions in designing a simulation which does not include all factors, but instead looks at only a single facet of the system. In this case, the model considered events which would make it impossible to meet demands or require the dispatching of another truck. A dispatching policy was modelled in detail, as were costs of using a spare vehicle and giving overtime (in an average sense). For screening alternatives, a simplified problem-specific simulation like this can be used to greatly reduce the space of possible systems.

The options which a model of this type can inspect are, of course, limited. These include the effects of different fleet sizes, and of different distributions of productivities -- both may relate to vehicle choice. Maintenance policies can be investigated through cost and repair time distributions. On the policy side, it is possible to look at the effects of different dispatching and crew usage rules, such as the amount of communications between the dispatcher and the trucks and the allowed amount of overtime. It is possible also to look at different demand levels to estimate the effects of seasonal demand variations. However, there are many options which are beyond the scope of the model; for example, changes in the actual delivery at the stop might change the aggregate productivities, but should be investigated in detail, either conceptually or through another model. One interesting area for analysis might be called the impulse response of the system: how well the distribution system responds to transients, or how long it takes the overload generated on a day to die out. In a heavily utilized system, an overload on one day would be expected to cause overloads on succeeding days. In an underutilized one, such effects would be expected to die out quickly.

In any model, the level of service and cost figures generated should be related to system objectives. Cost in this model is computed very simply: each truck used has a minimum cost, equal to crew wages for eight hours plus average vehicle operating costs; overtime is computed as demanded. Maintenance costs are a fixed minimum fee for each breakdown plus a variable cost depending on the repair time, although this variable cost has been set to zero for the first analysis. This reflects the assumption that maintenance is paid regardless of the number of trucks or breakdowns, and insensitive to the system option tested. All costs are accrued on the day in which they occur, and a table is plotted giving the distribution of daily costs and the average cost of the system.

Level of service is measured by the demands for collection delayed until the following day, and by the number of routes interrupted. These variables affect the demands for service and consumer acceptance of the system. Other variables concerning the service provided impact the operator. These include the distribution of loads given to the various trucks, the frequency of breakdowns and the repair times, and the number of interrupted routes, overall and per day. These variables are all computed and tabulated, as is the amount of uncollected waste carried over to the next day, which is given as a time series to look at the transient response.

Several structural assumptions are made about the collection system, which could be relaxed in more sophisticated versions of the model. All trucks are assumed to be identical, and all routes are assumed to have the same distribution of demands. Productivities (in terms of time per load) are identically distributed for all routes and trucks, so that one route does not get all the widely varying demands: these are spread throughout the whole system. The productivity assumption makes it possible to avoid modelling the distribution behavior explicitly, and should be checked since it greatly influences the behavior of the model.

Foremost in modelling importance is the dispatching and communications system, since it controls the response to these random events. In the present model, it is extremely primitive, with trucks sent in response to breakdowns or overloads if they are available and there is a reasonable amount of time remaining in the day. Breakdowns are called in immediately when they occur; overloads are described during lunch, when the driver reports his progress. Obviously, the dispatching policy would be much more complicated in a real system, but this example shows the characteristics of fairly bad communications and quick response by the dispatcher of many real systems.

The inputs to the model are fairly extensive, even if changes are not made in the dispatching or cost structures which are presently programmed into the simulation. First, the number of routes and number of vehicles must be specified. Then the characteristics of the delivery side must be input as functions: the distribution of the time between breakdowns; the distribution of repair times, and the distribution of times required per load including travel, pickup, and overhead. All this data should be available from agency records. The routes are assumed to be statistically independent, which can be checked. Wage rates, and limits on overtime and dispatching times, can be input by slight changes in model structure of key parameters.

Figures 3.1 and 3.2 give flowcharts on a macroscopic level for the two processes. In general terms, a vehicle waits in the depot until released by the dispatcher. Its demand is then computed, either from the demand functions at the start of the day, or from the remaining load of the interrupted vehicle, and the expected collection time is found. If the truck is overloaded, the dispatcher

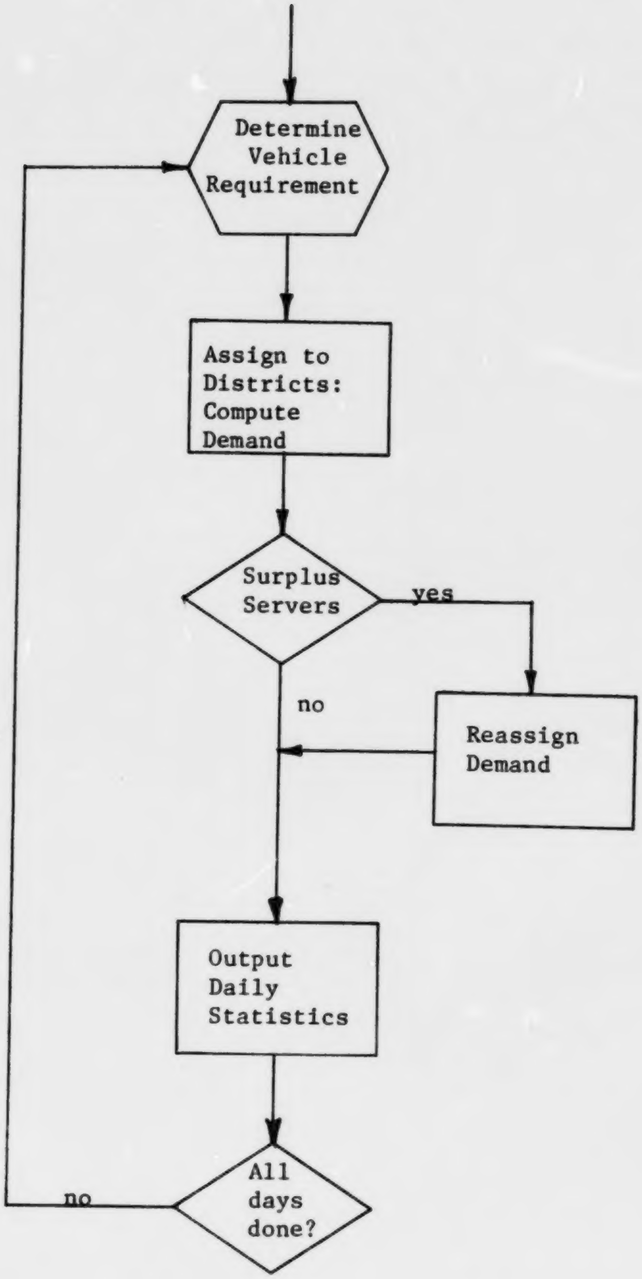
Determine Vehicle Requirement
Assign to Districts: Compute Demand
Surplus Servers
yes
no
Reassign Demand
Output Daily Statistics
All days done?
no

Figure 3.1 : The Scheduler Process

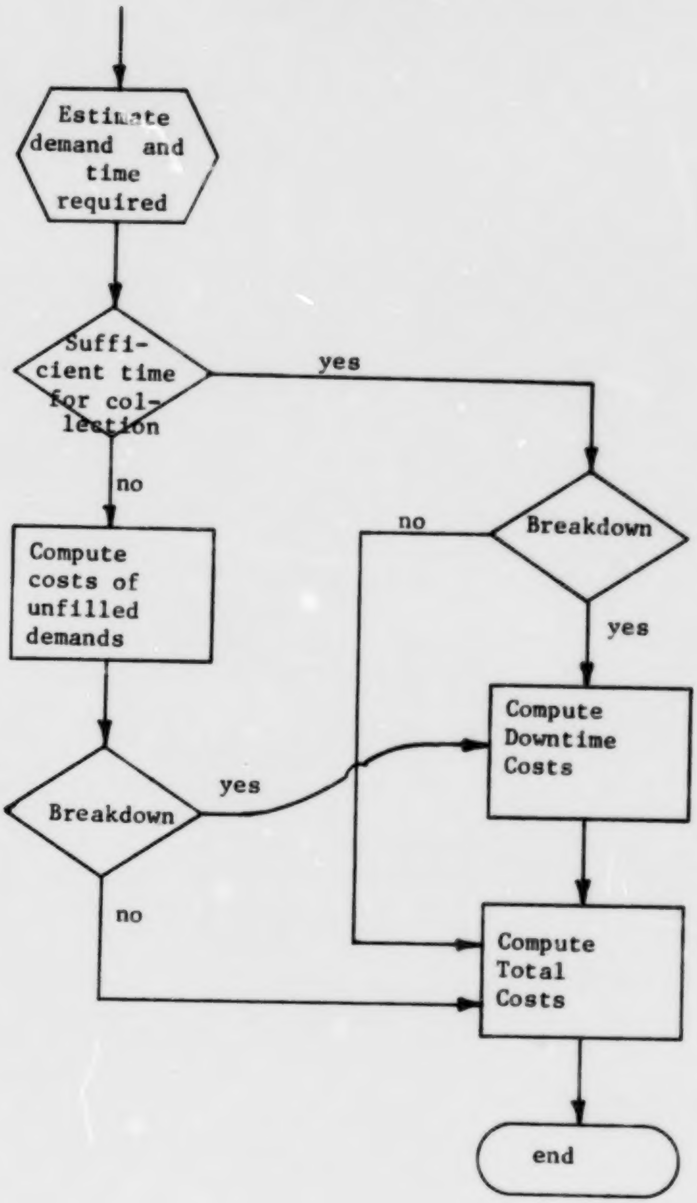
Estimate demand and time required
Sufficient time for collection
yes
no
Compute costs of unfilled demands
no
Breakdown
yes
Compute Downtime Costs
Breakdown
yes
no
Compute Total Costs
end

Figure 3.2: The Vehicle Process

is informed at noon and a new vehicle assigned. When a breakdown occurs, the dispatcher is informed and a new vehicle is assigned, with the old one staying offline until repaired. Replacement vehicles require time to get started, and cannot call for further help if overloaded. Costs are computed at the end of the day, as are the level of service measures.

In any model, care must be taken to avoid going beyond the structure assumed. For this model, limits include anything where the behavior of the trucks on their normal collection routes is important, and any system where the dispatching strategy is complicated beyond the point of assigning extra trucks. The latter is a possible extension; the former is a basic assumption made to make the problem tractable. Once this assumption is made, it is possible to look at system response to stochastic demands and breakdowns through a fairly simple simulation, without requiring enormous amounts of money or data.

3.4 Maintenance Policies

There are several options available for the maintenance of a fleet of solid waste collection vehicles. In real collection systems, one common policy is simply not to provide preventive maintenance, and to let vehicles run until they fail. At the other end of the spectrum of options are systems similar to those used by the airlines, with fully scheduled maintenance. Equipment vendors are also offering guaranteed maintenance contracts, where all maintenance is performed by the vendor and included in the price of the vehicle: these usually include preventive maintenance (7). In controlling the maintenance process and choosing what forms of maintenance should be performed regularly, important factors include the costs of keeping information on vehicle status, the costs of different levels of preventive maintenance, and the benefits received in terms of fewer breakdowns, less down time for the vehicles, and a longer equipment life. The American Public Works Association publication "Motor Vehicle Fleet Management" (6) suggests possible control policies and methods for preventive maintenance, as well as some ways to estimate costs. Their suggestions apply to both public and private fleets. Evaluation of the benefits received from preventive maintenance policies is difficult, though, so that it is hard to make a rational decision trading off costs and benefits of any particular choice. The important point is that measurement of the effects of the policies is crucial, and that modelling can be used to aid such measurement.

Consider a simple example: a system is operating with a preventive maintenance policy which requires inspections every X miles for each vehicle, where the mileage is measured from the last inspection or breakdown. The manager wishes to decide whether X is the right time between inspections, or whether a shorter or longer mileage would be more appropriate. Given a distribution of times between failures and some characteristics of the garage and the maintenance procedure, it is possible to use simple queuing models to estimate the number of vehicles awaiting inspection on the average, and the length of down time for each vehicle. Variables such as the gain in time between failures by increasing inspections can be estimated; increases in vehicle lifetime can only be guessed at. A study of the changes in down time by giving extra workload to the maintenance shop may give valuable data on excess capacity, and unused capacity has relatively a low marginal cost. Similarly, if the present system shows large amounts of queuing congestion, so that vehicles are standing around awaiting service for large amounts of time, one can estimate the gains achieved by increasing the time between inspections.

In large systems, a maintenance simulation model may be valuable. Such a model would take past data on the vehicles and attempt to develop indications of the actual decrease in breakdowns made by increased inspection frequency. Even more complicated issues like going from internal combustion to deisel vehicles could be analyzed. The cost of such models would depend on the detail in which breakdowns and repairs were modelled, as would the accuracy of the results. Still, even a simple model can be useful for testing alternatives and suggesting which ones are clearly worse than others. In maintenance, the goals are probably to get accurate cost estimates for new policies, and also to look at the effects of decreasing the down time per breakdown, increasing the time between failures, and even changing the usable life of the equipment. All these factors should be investigated; at present, the state of the art in maintenance models for solid waste operations is minimal, but there appear to be no conceptual difficulties.

3.5 Management Information Systems

One of the biggest problems in solid waste analysis is data. Very few communities or firms have an accurate quantitative idea of how their operation is performing. This is not meant to imply that they do not know what is happening: most managers know very well how their system works, and have an excellent qualitative grasp, but do not have the large amounts of data desired by analysts. Discussions with foremen are used where analysts might desire load weights, crew quitting times, truck miles, and other quantitative data. Still, there can be gains for the system managers from data gathering, if the processing is done to bring the information into a usable form. Load weights, for example, might lead the manager to expect a heavy week or a light one; truck miles might tell whether the routes are inefficiently designed, so that a large amount of time wasted driving could be spent in collection; quitting times might give an idea of workload equity for the crews.

Over the past several years, the management literature abounds with descriptions of management information systems, purporting to solve every problem which ever existed for daily operations. Much of this has been pure marketing by the computer industry. Nonetheless, several communities have developed solid waste management information systems with fair success. From the analyst's viewpoint, such systems aid research, since data is available for testing models; we cannot be viewed as totally unbiased observers. It is clear, though, that many systems lead to large computers costs and only bother the manager in his daily operation. It is also clear that in some applications the use of such systems has greatly improved operations. The problem is basically one of good design.

The design of the present generation of solid waste management information systems has been reported elsewhere (see, for example, Anderson and Roark (7), Clark (22), Lofy (80), and Limay and Blumberg (77)). Simple systems receive information each day about operations, and output digests at various time intervals (e.g. daily, weekly, quarterly), presenting the sorts of operating statistics usually put in annual reports ("In 1972, we collected 134,000 tons of solid waste, including 43,000 tons of garbage and 734 dead animals."). In a small or medium sized system, a decent foreman could do better, especially in describing daily operations. In the largest systems, a computerized bookkeeping operation like this may be necessary to keep management in touch with all phases of the collection and disposal procedure. Management information systems may also be combined with models to test the results of large scale changes, as has been done, for example, in Cleveland (25). In daily operations, the data generated can enhance the intuition of the operator or the foremen; they can be used to help a new worker develop an understanding of the way the system operates; and they can be used as a vehicle for comparing the perceptions of people seeing the operation from different points of view (e.g. the collection foreman and the maintenance chief). In other words, the data helps the people involved build, test, and communicate their understanding of how the operation works. All we can say at this time is that there may be some gain in daily operations through such a system, and that the gains in designing future major changes to the collection operation may be considerable. It all depends on the particular management information system proposed, however, and a skeptical view is undoubtably best.

3.6 Productivity

The problem of measuring productivity of collection crews is an important one, but one in which the impact of analytic models can be expected to be fairly small. Some indications can be drawn from analytical work which may be valuable, especially in large systems, but to expect models to replace observation and personnel management would be foolhardy.

Stone (121) shows a graph of the effects of fatigue on productivity. Also, as the week goes on, it is expected that the output per crew hour will fall, so that less waste should be available for pickup later in the week, if possible Although this is minor effect, it could be important, especially if the performance of one set of crews is measured on Mondays and another on Fridays. The daily fatigue graph is reporduced as Figure 3.3.

The concept of breaking down the collection task into a set of steps using industrial engineering efficiency measurement methods is an interesting one, and is being applied in Atlanta. The basic problem with this sort of modelling is one of confidence intervals: what must the difference in performance be between crews for the manager to be sure that a real difference exists, and that the result does not derive from stochastic variations or externalities such as neighborhood type. The main use of such productivity measurement may be to identify weaknesses in the system, such as trash-picking, or to estimate the effects of an increased desire for efficiency among the crews, as might occur with the adoption of the incentive system. Comparisons between crews are speculative at best, and modelling can lead to misleading results.

3.7 Weather and Stochastic load Variations

Variations in weather affect system performance and the demands placed for collection. The amount of waste may vary seasonally from about 50% to over 150% of the mean value, with individual weekly peaks much higher (see figure 7.1 for an example from one community (65)). It would seem reasonable, then, to consider both weather and the expected seasonal effects in allocating crews and vehicles to collect the waste.

Assume that as many vehicles and crews are available as necessary, and that routing is not a problem. If estimates of the effects of weather on productivity and waste generation were available, then it would be very easy to assign just the number of people and trucks needed to meet the expected load. In a real system, for example, it might be possible to use crews for solid waste in the summer, and snow plowing in the winter when less

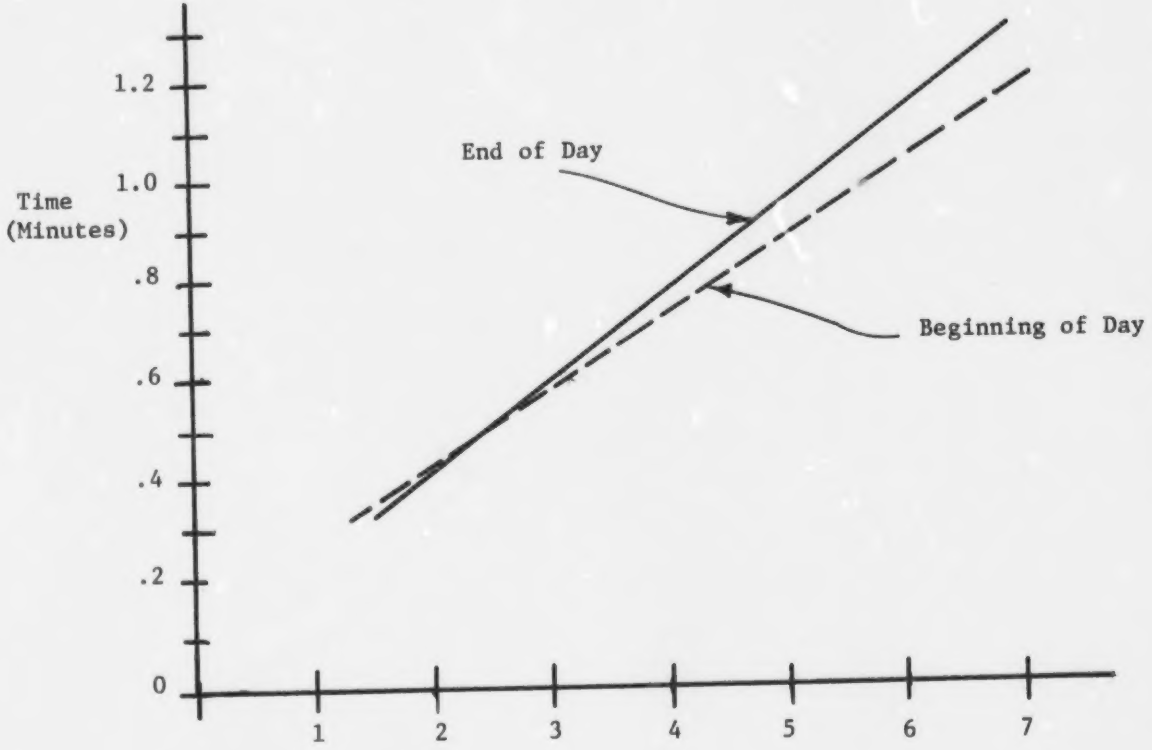

Figure 3.3: Decline in Productivity Over the Day

waste is generated. For daily operations, it might be possible to develop districts (or task assignments) for different waste generation levels and different travel speeds, so that a routing plan would be available for the average day, and other plans for slower and heavier days or faster and lighter ones. With flexible crew assignment, the routing plan would allow efficient use of all the crews by only assigning the necessary personnel to waste collection. This possibility depends on the specific characteristics of the system.

One approach is to statistically estimate the effects of weather on the collection process. This seems to be an important area for research. The problem is similar to the overload-breakdown work already discussed, and a unified framework might be desirable. The closest work is that of Lofy (80), who developed a method for assigning partial load areas to trucks and choosing haul points given various travel speeds depending on the weather. The method is a simple linear program which can be solved by hand in real time, so that it is possible to assign trucks to tasks at the beginning of the day according to the weather conditions and their effects on speeds. The method, though, does not consider workload equality or changes in waste generation.

3.8 The Interface with Longer-Range Options

Daily operations will continue to be a critical part of solid waste collection management, and an area where the application of analytical techniques will be limited by cost and the complexity of the decisions. There are three ways in which analytical models could be useful: in helping make a particular operation more efficient, in aiding the manager in understanding the system operation, and in providing a tool for investigating the effects of policy changes on the daily operations process. Examples of the first type are the routing procedures for bulk collection and the weather dependent routing developed by Lofy. The various simulation models mentioned fit both the second and third types, aiding in understanding both the system and the effects of changes, while the productivity techniques and the management information systems are primarily aids in comprehension.

To a large extent, the flexibility available in daily operations is limited. Choices of equipment, work rules, place of collection, collection frequency, and even of route are often made on a much longer time scale. Daily operations should simply maintain efficient operation under the constraints provided by these decisions. It seems to us, though, that very little investigation is done of the effects on daily operations of a decision to, for example, change from once weekly to twice weekly collection; this is an important area. There are undoubtably some combinations of middle range decisions which lead to very inefficient operations, and others which might lead to unexpected efficiencies. The next chapter includes a discussion of the medium range decisions and of some of the models which might be useful in estimating costs and effectiveness.

MODELS FOR LOCAL COLLECTION SYSTEM DESIGN AND OPERATION

The previous chapter mentioned that the problems of daily operations are highly constrained by longer range decisions establishing the services provided and defining the resources available for the collection task. This chapter will discuss those questions, and also some operational issues with longer time spans than those discussed above. Four basic interest groups determine the characteristics of the system: the collection managers, the citizens who require service, the local governement, and the collection workers. All interact upon issues such as frequency of collection, place of collection, work rules, crew size, equipment choice, separation of wastes, cost of the collection service, and vehicle routing. Certain of these issues are important in determining the level of service seen by the community, and others are important primarily from a cost and efficiency viewpoint. The decisions which directly concern the consumers of the service will be characterized as "planning" decisions, which are usually set by a political process with little interaction with the actual operational issues. These include place and frequency of collection, separation of wastes, and financing methods. Decisions such as work rules, crew size, equipment choice, and routing and vacation scheduling are more operational in nature, and will be described after the planning issues.

4.1 Planning Issues

In designing a solid waste system, it is important to consider a number of impacts from the service. Sanitation is necessary in an urban community. If the impacts of putrefying garbage only accrued to the generator of the waste, it would be reasonable to allow the free market to provide collection and disposal service. Those without satisfactory methods for handling their wastes would contract with others. However, one person's waste may have significant effects on others, so most communities provide sanitation to guarantee an acceptable environment. There are also significant economies available from consolidating collection for an area in one supplier, such as a Public Works Department (19).

Sanitation standards vary from place to place, but most counties or states have a minimum required collection frequency, usually based on the fly breeding cycle, for putrescible wastes. Since there are significant economies in combined garbage and rubbish collection from a sanitation standpoint, but the best that seems possible at this time is a qualitative "Higher frequency, cleaner area." This naive model is suspect: higher collection frequency probably leads to more spillage, and has significant impacts in systems with curbside collection on odors and spillage.

Resource recovery may change the design of solid waste collection systems significantly. Separation of newspapers or glass could greatly increase the problems in designing a collection system. It is easy to see that costs would rise greatly if multiple vehicles were used, each with a single type of item to collect. The other alternative, though, is a single compartmented vehicle. A precursor of this sort of system is in operation in Madison, Wisconsin, where special racks have been added to the collection trucks for carrying separated newspapers (8). The problem with this is that haul must be done whenever either the truck is full of normal waste or the racks are full of papers. (The alternative of mixing newspaper with other waste once the special compartment is full defeats the purpose of the project). Since the amounts of each type of waste are random, efficiency is lost because one compartment will almost surely be partly empty when the other is at capacity. In Madison, the newspaper racks filled much quicker than the truck bodies, so special dumpsters were set out around the community to serve as short-term transfer stations for the newspapers. Even the best design for compartmentalized vehicles will lead to lower collection productivities than a single compartment vehicle of similar total capacity.

Aesthetic issues and other non-sanitation environmental issues may be important in some contexts. Curbside collection, for example, is accepted in most urban areas in this country, but is not in most European communities (29). "Dustless" collection vehicles are common in Europe for minimizing pollution from spilled waste (39). Noise may be a factor, especially in choosing collection vehicles and setting collection times for different areas. So may street congestion and parking problems, in densely populated or highly commercial areas. Congestion tends to be more important in street cleaning than in waste collection, but may be a factor in collection time.

The method of financing affects the user perception of system cost, and may, therefore, be important. A collection system totally supported out of the tax levies will be viewed differently than one dependent on a special service tax or user charge. Use of user charges may also have important effects in denying some people the possibility of having their waste collected, or forcing them to discard it as litter because of direct collection costs (87). If the Public Works budget is only a small component of the tax load, it seems likely that there will be little incentive to minimize costs since there will be little feedback from the community. On the other hand, major controversy often occurs on capital budgeting issues, such as a processing plant or new vehicles. If a direct user charge is the fund raising method, feedback on rates will be more continuous, incentives to cut cost will be stronger, and capital projects funded from the user charges will be possible. However, some mechanism is necessary to make sure that all residents can use the service. It may also be desirable to allow competition to occur in some areas (such as commercial collection) to serve as a further incentive to efficiency (92).

The solid waste collection system interacts with the residents of the community in a number of ways. Most of these are what might be called "level of service" variables -- measures of effectiveness for environmental and aesthetic objectives. Others interact somewhat with the efficiency measures, such as the cost of service and the probability that the waste may not be collected on the desired day. All are important and should be considered in designing a collection system. In making major changes to an existing system, though, there is another important aspect. The solid waste level of service varies widely between communities, but the number of complaints tends to stay relatively constant. People tend to accept an operating system, and to react strongly only to changes in the status quo. For this reason, it has been difficult in Brookline to combine garbage and rubbish collection, even though only a small fraction of the community presently separates their waste. Even in something as simple as rerouting the trucks, changes in the day of collection for some residents may limit the potential for other innovation. The political issues in performing the change are too large, and changes in service level may be infeasible.

4.2 Planning Options and their Effects

There has been a reasonable amount of literature written on the effects of planning changes on the costs of solid waste collection, and some work on the actual environmental effects of the planning changes. Most such work involves frequency of collection, since this is a simple discrete change which does not greatly affect operations. For example, Marks and Liebman (84) and Truitt, Liebman, and Kruse (131) investigate the effects of increasing the collection frequency for Baltimore on the cost of the service. Both optimization and simulation models are used, and the results appear to be fairly accurate. Coyle and Martin (29) and Martin and Rothwell (88) look at the effects of specific collection points on efficiency (for example, comparing curbside bag collection with rear-of-house) and develop estimates of changes in cost. Marks et al.(86) investigated the collection system of Cambridge, Ma. and discovered that the "barrel-rollers", who carry out the waste of supposedly disadvantages residents for collection, actually provided service to the most affluent and politically important segments of the community, and not to the aged or physically disabled population. Stone (119) compares bag service with curbside can collection for several areas, with respect to both cost and environmental effects. Most of the work, however, has been based on efficiency, and little consideration has been given to the question of how a planning change will affect the service provided to residents.

Quon, Tanaka, and Charnes looked at an area in Chicago which converted from once-per-week to twice-per-week collection, and measured the quantity of waste collected before and after the change (106). The results show significant increases in the amount of waste. Since it is unlikely that consumption changed very much, this waste is probably material which would otherwise be thrown out in other ways, perhaps as litter or through the sewer system from garbage disposals. This is one of the few results showing the effect of planning changes on the general community environment. Unfortunately, little was done with respect to comparing the amount of litter in the area, and no real measure of environmental health was undertaken. Still, the work demonstrates that planning decisions can have real impacts on the quality of the community environment.

In New York, the air pollution and noise from collection vehicles is an important issue. While transfer stations are economical for even fairly short haul systems, the reduction in air pollution from the haul portion of the collection process is an important social benefit (33). On the other hand, both noise and pollution will be concentrated in the neighborhood of the transfer station, which may not be acceptable.

The introduction of separation systems may be an important issue, especially with the reduction in available landfill space in most communities. In such systems, though, the service provided must require little extra effort by the resident if a significant amount of the potential reclamation is to be achieved. Here, a system like Madison's which requires only separation and storage is likely to work better than that of Wellesley, Mass. where the materials must be taken by the resident to a central location (8,13) In fee-for-service systems, rebates for reclaimed materials might be possible as an incentive. Naive prediction of the potential amount to be reclaimed is done by procedures such as estimating the amount of glass entering the community and guessing at a "probable" amount recycled (13). As data becomes available, it may be possible to apply modelling techniques such as those used in predicting transportation model splits (73,122) to classify households according to the likelihood that they will separate and reclaim their wastes. Estimation of the expected amounts recycled under various systems might also be possible. Note that these models should attempt to be causal; that is, they should not just extrapolate trends but instead attempt to work from some theoretical basis explaining individual behavior to develop estimates of individual actions.

System cost is clearly an important aspect in the level of service received. However, it si somewhat separate from the more environmental effects since it is less directly connected to the service perceived. Even in a user charge system, the cost of the service will probably not be directly connected with the service itself, except when rates change. An individual household is not likely to explicitly trade-off the sort of waste collection they receive with the cost of that collection, except in special cases. These cases include the poor who can not afford the service, some elderly who would be willing to pay to avoid having to carry their waste out for collection themselves, and others who find various types of barriers to using the waste collection service. A municipality seldom offers different levels of service to meet different needs in the community; it seems likely that commercial waste is handled by private haulers partially because of more appropriate service offerings. The feedback between costs and service is difficult, and tradition tends to be much more important than cost, thus reducing the possibilities of implementation of many innovations. At the planning level, cost of service is probably more of a constraint than an objective, with design tending to be done to minimize cost under a particular configuration of collection frequency and place, sanitation standards, and financing mechanism. Once these decisions are made, either through analysis or by the political process, it is possible to design the system to maximize efficiency in resource use and to minimize the costs of providing a certain level of service.

4.3 Equipment Choice and Crew Size Decisions

The management of collection crews to maximize productivity is a very important aspect of solid waste operations. While the actual management takes place at the daily decision level, it is important to look at the effects of different types of policies on costs and outputs. Note that this discussion will be based on a predetermined level of service required by the residents, setting collection frequency, place and time of pickup and other variables. The operational decisions of how to provide this service efficiently can be broken into two areas. The choice of type of equipment and the crew size for operating that equipment is one basic decision. The choice of the work rules under which those crews will operate is another.

Previous models used for analysis of these questions have had fairly simple goals: estimate the costs of different options which will provide the desired level of service, and attempt to choose that option which leads to the minimum total cost. Clark and Helms (24) developed an optimization model for investigating the choice of new vehicles for a community. Larger vehicles require more capital, but reduce the time spent on haul during the day, so that more waste can be collected. Because the length of the workday was fixed in their example, the average amount of waste collected per vehicle day depended primarily on the amount of time spent in collection, which in turn depended on the haul time and the number of loads. An ideal vehicle for such a problem might be expected to complete, on the average, an integral number of full loads per day; haul would not be necessary with a partially full truck. Frequency of haul is assumed to grow linearly with volume. More important, no consideration is taken of stochastic effects. The cost assumption is probably reasonable for a first pass, to suggest whether 20 yd. or 10 yd. vehicles are better. A detailed simulation could then be used to evaluate the results. The lack of stochastic considerations, though, is troublesome. Designing the system for mean loads may lead to overtime payments in several months of the year. The seasonal pattern of waste generation should be taken into account in deciding what level of waste is the base for the system (see chapter 7 for a further discussion of this point). It is often important to design in some slack so that daily and weekly variations may be handled. Consider a truck which, on the average, gets filled twice per work day, and another which gets filled only one-and-one-half times. The smaller truck will have to make a third haul whenever the load for the day is above average, while the larger will make the extra haul only in extreme cases. The variance in the daily loads is an important factor in choosing the best truck size. Externalities also exist: maneuverability may be important; a container system may require special handling equipment, etc..

Perkins investigates the use of satellite vehicles, and develops some cost estimates for their use under different types of systems (102). The simulation is based on pickup density and similar factors, and analysis is done to determine the efficiency of different work rules (e.g. whether the driver of the mother truck does collection). The results appear reasonable and could be useful in deciding whether a satellite vehicle system could be applied in a new location. Much work on new technology applications focuses on analyzing the costs of an existing pilot system. However, models can be used to estimate some of the causal effects operating which determine whether a technology would work well in a new location. Frequently conventional cost analysis is performed.

In other cases, though, production function models may be valuable.

Stone, et al. (121,119) have performed two important studies of new collection technologies. The first concerned the use of different crew sizes, and developed estimates for costs and performance under varying conditions. The bulk of the study was cross-sectional analysis comparing systems in several communities. Crew size is a fairly easy decision to work with, since the choices are limited. Perl(103) develops a simulation of different crew sizes for France, estimating costs and productivities interactively with the choice of equipment. This sort of work is easy to perform and can give decent "first pass" results. Detailed analysis can then be performed on the most attractive solutions. Examples of the costs of excessive crew sizes are shown in the work of Clark and Gillean (25) and Marks, et al. (84). The second Stone study involved the adoption of plastic and paper bags for collection(120). While no model was developed of increased efficiency, cost and productivity analysis was done for one community in an experimental setting. In most cases, though, such experiments are impossible in the social context, and models must be used.

Labor costs will continue to rise faster than capital costs. This may lead solid waste systems to shift toward more capital intensive collection techniques, whether automated vehicles such as have been developed in Scottsdale and other areas (124,123,98,51) pipelines (93) or simply one-man vehicles as described in the Stone study. We do not know of any analysis on the suitability of such new technology in urbanized areas subject to snow and other problems (such as parked and double-parked cars, for example). However, suitable mechanized collection vehicles are probably going to be available soon. It also appears that much of the new construction will use pneumatic pipeline collection systems (93). Welfare Island in New York is such a development (44). Analytic approaches towards choosing the optimal technology are an important area for future research.

The problem of choosing equipment and crew size is going to be more and more important as the options available increase. Simple models such as those described here for estimating the efficiency of various combinations will be necessary to limit the possible options before decisions can be made. A detailed analysis of all the alternatives will not be possible in all cases, because of limited resources. Models can be used as a real aid to decision-making by reducing the number of options to be studied in detail. Note that the requirements for using such models are not large. For example, a programmable desk calculator could perform simple simulations of the type described. Since the factors involved in the decision may be fixed or varying depending on the particular system, it would be foolhardy to try to develop one model for all applications. It is more reasonable to suggest the important interactions and effects so that the issues will be clear to users in real operating environment.

4.4 Work Rules

The choice of work rules for collection crews has been the focus of a large portion of the modelling involved with community collection systems. There are several reasons for this focus. Work rules are important, since they often determine how efficiently the system can operate (5). There are a wide range of options available, from many types of overtime allocations to all the variations on the incentive system, and even to topics such as vacation and shift scheduling. The labor intensive nature of collection makes efficient use of manpower resources critical. At the same time, the large number of actors involved makes the problems too complex for most people to have a good intuitive grasp. This makes work rules a natural area for the application of modelling techniques. Of course, little of the work has been concerned with the implementation of the suggestions, so that the real problems of bringing about change in the bargaining process between the unions and the system managers have often been ignored. Money saving techniques in solid waste collection often are primarily job-saving techniques, and innovations of this type may be difficult to bring into practice.

Wersan (138), simulated two collection systems in Illinois and tested the implications of changes in the operating policies, especially with respect to work rule changes. The first system, in Winnetka, used a daily route (or "incentive") system, where tasks were assigned to each crew at the beginning of the day, and crews were free to leave at full pay when the task was completed. This system can be expected to lead to quicker pickup, but less consideration for spillage than a total hours method. The policies investigated were of the "relay" type, where the whole crew does not travel with the vehicle for the haul when full. Instead, a second vehicle joins the collection crew and their time is not wasted in travel. The result is improved utilization of labor at the cost of extra vehicles. In most communities, though, relay policies are not feasible because of labor constraints. The second simulation concerned a total hours system in Chicago. In a total hours method there is less incentive for the crews to finish quickly, so that less waste may be collected per crew hour. However, more time is likely to be spent in avoiding spillage of waste or in waiting for residents to get their waste ready for collection. Policies investigated here involved changes in collection frequency and the cost of such changes. In comparisons made between the two systems, it is interesting to note that the variance in the amount of waste generated seemed to be an important factor in determining what set of work rules were best. Note that haul distance is also important, and may be set exogenously by the limited number of disposal options available.

Tanaka, (128) developed an optimization model for looking at the allocation of overtime. He assumed a stochastic variation in the amount of waste available and the productivities of the crews. He investigated both overtime assignments under total hours systems and incentive plans, as well as hybrids. The cost function was a combination of total direct cost and an increasing function dependent on the missed collections -- the waste remaining on the street at the end of the day. The model works on a weekly basis, so that waste left over one day must be collected the nest. Runs were done comparing alternative policies under various conditions on waste generation, productivity, and cost. The model is simplistic in many ways, but may be valuable in some contexts.

One aspect of work rules which seems very amenable to mathematical analysis is the question of shift and vacation scheduling. In New York, Altman et al. and Ignall et al. (64) formalized the problem of choosing how many men would work on each shift to minimize costs, subject to major constraints from the sanitation mens Union. It proved possible to maximize long weekends while meeting demands, and to reduce Sunday and holiday work. Both the amount of waste collected per dollar, and the working conditions of the men were improved. Heller (55) and others have also developed methods for organizing vacation schedules of single- or multi-shift operations to give much better assignments. In some solid waste systems, of course, vacation assignment is simple. When the desired vacation time (usually summer) coincides with the lowest loads, it is possible to give vacations while still keeping sufficient personnel to handle the work without overtime. In more complex situations, though, models can help achieve obvious goals by performing the necessary mathematics. Heller's methods in particular are easily done by hand for groups of up to twenty or thirty men, and give excellent results at extremely low cost.

A model of the costs of injuries could be useful in many solid waste operations. Injuries and lost time are primarily issues for daily operations. Still, the design of the system and the work rules are important in influencing the injuries which may occur. As far as we know, all models developed so far include injuries only as externalities, and are, therefore, somewhat "best case" analyses. This may be an important area for future research.

The models described above, while limited, can be used to get a reasonably good idea of how the different types of work rules operate in practice. Many sorts of policies are available, and it seems desirable to test such policies with inexpensive mathematical models before actual implementation. It seems likely that some configurations are inherently less efficient than others (e.g. back of house pickup with daily route would probably be less efficient than with weekly route), and identification of the best set of configurations from a cost standpoint should be done if possible. Mathematical models enable the designer to test alternatives to some degree without expensive and time-consuming real world experimentation, and the set of choices available in work rules decisions suggests that such testing is desirable.

4.5 Routing and Districting

The choosing of "optimal" collection routes has been the focus of large amounts of highly mathematical research in the past few years. There are two major reasons for this research: first, routing seems to be an important problem, and second, it is an interesting one from a mathematical viewpoint. In fact, routing problems for delivery type services have been a constant area of interest in operations research. Much of this project has been concerned with this area, dividing the problem into two basic parts: the design of efficient and equitable daily collection tasks for the crews, and the routing of the vehicles through those tasks. In actual systems, these resource allocations take place at several levels. Assignment of the daily tasks for crews can range from the collection of a fixed district down to a simple "Go out for eight hours and collect at least two truckloads of waste." Routing may be fixed beforehand or at the discretion of the driver. We feel that a fixed set of basic districts and routes cannot reduce efficiency, and may save time by requiring less travel over the day. Time saved in travelling may be converted into extra time for actual pickup. Chapters 5 through 8 consider the problems of routing and districting in detail, and include a review of the relevant literature. It is the purpose of this section to show the connection of these problems with the other issues in planning and long range operations.

The problem of deciding which vehicles should collect from which areas in the community, and of how they should be efficiently routed is a universal one. While the waste generation may vary from community to community, and the travel speeds and collection productivities will change from system to system, the necessity of dividing up the collection task remains. There are two exceptions to this generalization: areas without truck collection, whether handled by the resident or by some means like pipelines; and, areas which comprise a single natural route, such as a community which uses a single truck one day a week. Conversion away from truck collection will be slow because of the high capital cost of pipeline systems.

The major effect of district and route assignment on the other planning and operations issues comes through efficiency. For example, if 20% of the crew's time is spent in travel between widely space collection points and this were reduced to 10%, the result would be an effective workday increase of about 45 minutes (assuming an eight-hour day). The length of the effective workday makes a major difference in the choice of equipment and work rules, and increased districting efficiency may make a reduction of personnel possible. It is also clear that a system which assigns new collection points randomly (or, perhaps, to the crew which presently has the lightest load) may cost much more than is necessary. To make accurate estimates of the optimal equipment and work rules, the tradeoff between travel and pickup should be looked at explicitly; districting is one method for doing this.

Conversely, the planning and other operations issues greatly effect the districting, as do some of the daily management issues like productivity. The amount of waste generated per household and the place and frequency of collection are extremely important. Districting size also depends on the haul time from various sections of the community, the equipment used, and the work rules and crew size. The basic measure of a district is that area which one truck (or crew, in relay systems) can collect in a day's work, given the waste generation at that time of year for which the design is being done. If the district size can be estimated, this gives important information on how many routes and districts will be required, which in turn implies the amount of labor and number of vehicles necessary.

Routing depends greatly on the districts chosen. Improved routing on good districts can only save otherwise lost travel time -- the covering of streets extra times in getting between one street which has waste and another. It may also be possible to save at intersections, but this too is minor. Routes can not also be totally fixed: consider, for example, the effects of street construction. The detailed routing, given the area to be collected, although not too important, is relatively easy, so that near-optimal routes can be generated at low cost. Districting, though, is an important key to efficient operation.

4.6 Management Information Systems and Data

In Chapter 3, it was suggested that the most important issues for management information systems were in the longer term operations, as opposed to their daily use. Accurate data is the most important issue in system design: without it, all choices are at best guesswork. With it, the intuition and experience of the system managers can at least be checked, and possibly enhanced. Everybody knows that waste varies seasonally, but very few systems have an accurate idea of how much real seasonal variation occurs. The efficiency of recycling programs in reducing the waste processed cannot be checked except by accurate records. District design could best be done by using the time stream of amounts collected from different areas in different years. Data on collection times per ton could suggest how different types of equipment operate in practice, as could maintenance records. Projections of the amount of waste expected over the next several years really requires data on the waste generated over the past several, perferably with composition information and data on the growth of the community as a whole. Such projections are important in computing the men and equipment required in the future (i.e. the budget). All of this data is "information." The proponents of management information systems for solid waste suggest that storing this information in a computer can: 1. save money, 2. keep the data available, and 3. aid the manage in using it. While these claims may be somewhat exaggerated (especially claim 1), it is clear that the data can be valuable, and that the design of a set of requirements for a management information system for a community can be valuable. Whether or not a computerized system is desirable, careful analysis of the data which can be collected and which could be used may suggest important changes in data handling. It is our impression at this time that most of the data collected in solid waste systems is not really used, and that some of it could be extremely valuable. However, computerized management information systems may not offer a better method for storing and handling the data. It seems important to rather investigate how the data is handled, and what better methods might be available -- either for data collection or for processing it into something useful. Data cannot replace good management, but it can be an aid, especially in computing and explaining such things as the budget.

4.7 Interactions Between the Various Levels of Decisions

It has been assumed that haul distance is basically exogenous to community collection systems. That is, haul distance is determined by the locations of feasible sites, and the designers of the collection system have little control over their haul point. A town incinerator may be closed, so that waste must be shipped to a regional landfill, for example. It is probably a truism that haul distances will not get shorter. There has been research on the idea of transfer stations, and on at what haul distance they become economical. Since transfer is often desirable with hauls of less than ten miles (from some "centroid" of the community), it seems likely that most urban communities will develop transfer stations over the next decade or so. The development of the system would be an ideal time for a major change in the system for choosing the level of service desired (see, for example), the Fresno study (2), and the equipment and work rules for a significant period of time. If planning and long-term operations decisions are undertaken at a different time, the effects of increasing haul distance should be carefully considered. In Madison, for example, full rerouting was not done because the high cost was unreasonable given an expected change in haul point three years later. Routes designed for the shorter haul would not have been suitable for the longer.

Many planning and long-term operations decisions are made without any thought of their effect on daily operations. Daily operations concerns the handling of random events which affect the system: what to do when a truck breaks down, or when the loads are extra heavy, for example. The longer term models usually assume a "best case", with a set of assumed loads and everything working perfectly. Inclusion of the effects of stochastic changes in system operation into the longer-term operations models and the planning decisions is an important area for research, and one as yet univestigated. Designing flexibility into the system is critical, yet little of the research has investigated this topic.

The work performed under this contract is discussed in the following set of chapters. At the community level, a low cost system for districting and vehicle routing was developed. The key here is flexibility. The areas collected on any particular day should remain invariant, at least in a curbside system. However, a cheap method for generating districts and routes would enable the system manager to efficiently use a varying number of trucks and crews, by simply generating several alternative sets of routes. The number used and the district set could depend on varying travel times and waste generation factors (e.g. the week after Christmas would have districts designed for slow travel and high loads). The present routing methods all assume that the wasteloads will remain invariant over time, as will the routes. This is not justified, and can lead to a series of myopic modifications until single trucks are collecting from individual street segments all over the community in a single day. The districting program, and its data base, can also be used for testing the effects of different planning changes and of varying work rules, if estimates of the changes in productivity and/or waste generation can be made.

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DISTRICTING METHODS

A major forms of our research has been on methods of designing task assignments for collection crews. The various planning characteristics and resource constraints described in the above chapter are taken as given, and the problem becomes one of partitioning the community into a set of efficient assignments (or collection areas or districts). There are a large number of goals involved in what makes an efficient district and the "optimal" set may vary from person to person. We have not tried to define the "optimal" set of districts, but have instead attempted to simply generate a satisfactory set. The gain by using some sort of optimality approach would be small, especially in comparison to data errors, and the extra cost made any such attempt infeasible.

The reminder of this chapter will be concerned with the districting problem, and primarily with the application of algorithms developed for political redistricting to solid waste collection. In the final section other uses besides routing for the districts will be discussed and some suggestions for future research developed. First, though, it is desirable to look at the districting problem in detail.

5.1 Goals for Solid Waste Districting

The criteria for acceptable and "ideal" districts for solid waste collection can be expected to vary between systems. Size, of course, will vary depending on the service provided and the other operating policies. There are a number of other important aspects, though, which are also dependent on the system goals and characteristics.

Equity is extremely important in many systems. If an incentive plan is used, it is critical to have the various districts require equal workloads, whether this is measured by time or by the amount of waste collected. Inequities will lead to some routes being preferred to others, and possibly to significant labor problems. Inequities also reduce the flexibility of the whole system and the maximum capacity which can be handled in a single workday. Workload can be very hard to measure, especially if fatigue is taken into account. In total hours systems, workload equity may be less important, to the extent that fixed tasks may not even be assigned.

Compactness is another possible measure of districts. In a compact district, boundaries are minimized and the whole area is a single, nicely shaped lump. There may be some advantages for routing in using compact districts, although this is not clear. Compact districts, though, may give management a better idea of what areas have and have not been completed, and may minimize the interactions between crews by reducing intersecting boundaries. A set of compact districts also looks intuitively "good", and can be used to explain the system to residents. Note that it is probably important to have the daily collection areas (for all trucks combined) compact, to minimize the problems to residents in learning when the waste is collected for their home. This is especially important in curbside systems, where each area may only have to endure the esthetic disbenefits once per week. In node collection systems, the advantages of compact districts are large (33).

Contiguity, while somewhat subsidiary to compactness, is important from an efficiency viewpoint. Districts composed of two or more disjoint pieces are troublesome, since time may be wasted travelling from one to another. The addition of new sections to old districts has probably been a major cause of the routes presently in use, where large portions of the day are taken up by unnecessary travel between sections. Noncontiguous districts may be acceptable in some applications, but are a very dangerous precedent. (See figure 5.1 and figure 5.2).

Districts should be designed to consider the various types of equipment available: if the community has 20 yd. and 12 yd. trucks, two different district sizes should be constructed. The policy for covering loads left on the streets overnight (if any) should be explicitly considered, as should constraints on the time of day when collection is possible. For example, a business district might be supposed to be collected before 9 a.m. This would be impossible if the whole area was one district. There are other important issues, and the transformation curves between the various objectives are not simple. Still, it appears that the three major objective of compactness, contiguity, and minimum variance in workloads, if satisfied, should lead to acceptable solid waste collection districts. (It is also desirable to minimize the generation of new odd nodes, as described in Chapter 6, but that is beyond the scope of this discussion).

The important fact about these three objectives is that they are directly transferable to the Political Districting Problem, which has received significant research. The Political Districting Problem is to generate a set of election districts which satisfy the one-man-one-vote rule (population equality) and are not gerrymandered (contiguity and compactness). The main goal is to equalize the populations of the various districts, while producing simple shapes with each district in one piece. If the "population" of the election district is replaced by the "workload" of the solid waste district, the methods appear compatible. The political districting techniques are based upon simple population units, such as counties or neighborhoods; solid waste districts are

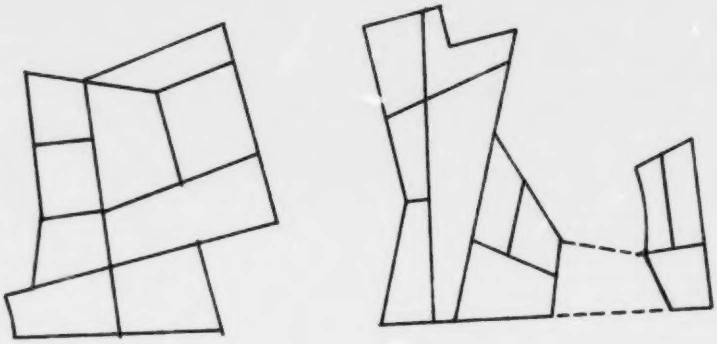
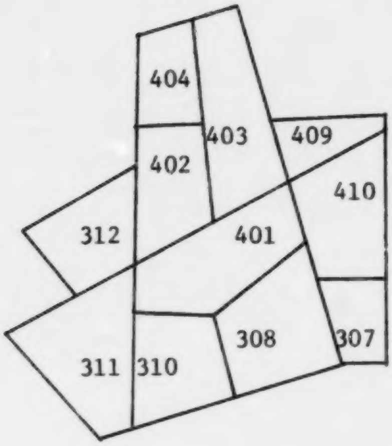


Figure 5.1: Contiguous (a) vs Non-Contiguous (b) Districts


404
403
409
402
410
312
401
308
307
311
310

Districts Contiguous to Cell 401: 311, 310, 308, 410, 403, 402.

Figure 5.2 Sample Contiguity Listing

based on loads from households, streets, or blocks. Again, the transferrability seems to hold. The research described below discusses attempts to use two political districting algorithms to generate districts for solid waste collection, with reasonable success.

5.2 Political District Literature

Significant research has been done on methods for solving the political districting problem over the past several years. Because of cost considerations, most algorithms have been heuristics. That is, they use "common sense" rules to generate good solutions, but do not insure an optimal answer.

WEAVER, HESS

The first attempt at districting was a heuristic program developed by Weaver and Associates at CROND, Inc. in 1963 (57,136). The program, REDIST, was later used by Mills (94) in England in 1967. The REDIST program uses the idea of a warehouse location problem as a basis, but due to the inadequacy of the warehouse location techniques available, the program was built around a transportation code (Hess, 1965). In relationship to the transportation problem (where m supply points have items to be shipped to n warehouses) population units serve as sources and the trial district centers as sinks. If the demand at each district is set exactly equal to the average district population, some population units are split and have to be recombined. The cost to be minimized is the population moment of inertia or the sum of the squared distances between each person and his district center. The population moment of inertia can be approximated by finding the squared distances between the geographical centers of the population units and summing these for the entire district. The population moment of inertia also measures the relative compactness of a district. One problem with using a moment of inertia for a measure of compactness is that it tends to bias the results towards districts made up of larger population units. Population equality is only implicitly considered in the minimizing of the population moment of inertia.

The heuristic can be summarized as follows:

1. Select trial legislative district centers
2. Compute a matrix of the squared distances between population units and legislative districts.

3. Solve the transportation problem with the population units serving as sources and the trial legislative district centers serving as sinks.

4. Recombine the split population units so each population unit is assigned to only one district

5. Compute the moment of inertia for each district. Compute also the new population center of gravity for each district.

6. Repeat steps 2 thru 5 using the new district centers as sinks until two successive solutions are the same

7. Repeat steps 1 thru 6 with different initial guesses of population centers.

REDIST is relatively fast and able to solve fairly large problems. A disadvantage is that the results depend greatly upon the choice of the starting centers. Minimum disturbance of current district boundaries and homogeneity of the resulting district can be obtained by REDIST by a careful choice of starting centers (20).

An interesting extention of the REDIST program has been developed by Stevens (20). Stevens, a member of the Massachusetts House of Representatives and visiting social scientist at M.I.T., developed a time-sharing version of REDIST which utilized a cathode ray tube. The advantage of this method is that a person can observe a districting scheme on the CRT screen, decide what changes can be made, type in a command and the results of this scheme should be promptly shown on the screen.

THORESON

Thoreson developed a simple heuristic which amounts to little more than the enumeration of some of the feasible districting plans. A brief summary of the heuristic follows:

1. Pick an arbitrary population unit, A

2. Determine the population unit B, which is furthest from A

3. Build up a district around B by adding population units until the average district population is reached

4. Choose another "B" from the remaining population units as before, and build around B, and so on.

This is the basis for the IOWA program used in this project.

Compactness is measured by adding closest units first, but population equality is the prime objective. The program has had many features added to this simple base to improve its performance, including tests for "enclaves" (units not yet assigned, but unreachable from other assigned units) and "multiple enclaves". In using this algorithm, we have modified it to increase the emphasis on designing smooth districts at the expense of some population equality. One of these modifications involved making it impossible for units to be removed which would leave another unit only contiguous to the district at one point. This eliminated some peninsulas where a string of units might extend from the main body of the district. Another modification allowed districts to be accepted with loads slightly below the quota, to eliminate the revision process completely. Flow charts of this algorithm are included in Appendix B.

HELBIG

A districting method based on successive applications of a Hitchcock transportation problem has been developed by Helbig, Orr, and Roediger (54). A moment of inertia approach is used similar to that developed by Weaver and Hess (136),although simple distance could also be the objective. The algorithm attempts to reach good solutions by assigning population units to district centers to minimize the weighted cost. Since the density of people is not uniform, though, it is necessary to adjust the number of units assigned to each district center, which is a constraint of the transportation problem. After each assignment, the largest population district has its quota of units reduced by one, and the smallest has its increased by one. This iterative heuristic quickly minimizes the population variance.

The algorithm is by far the simplest so far developed, but it has two weaknesses for solid waste applications. First, it requires a fairly uniform population density, so that it would work excellently in a homogeneous community but might not succeed with wide variations in block sizes, as in Brookline. Second, since there is no explicit modelling of the contiguity constraint, the odd shapes of many blocks would not be considered and the district boundaries would tend to be uneven. Still, it is a simple algorithm to program and to use, so it could be very valuable in many situations. Especially useful would be the sensitivity analysis capability given by the linear programming (LP approach) and its dual variables.

An LP extension (the Hudson model) was developed during the course of the project, using the sensitivity analysis capabilities. Two objectives were used, and transformations between them developed. First, total assigned distance was minimized. Then the second objective, minimization of population deviations was introduced. This led to splitting N-1 population units, where N is the number of districts to be generated. The algorithm is simple and fast, but has the same problem with district centers as the other LP-based routines.

GARFINKEL and NEMHAUSER (1970)

Garfinkel and Nemhauser use (43) a two-stage "tree search" algorithm which will find all optimal solutions for a given set of criteria. Phase I generates all feasible districts using an implicit enumeration algorithm and Phase II uses the districts from Phase I to solve for the global optimum or optima plan. A districting plan is one where all population units are used only once and the plan satisfies all the criteria. Garfinkel and Nemhauser (1969) used a set partitioning procedure (set covering with equality constraints) to complete Phase II. The two phase approach to districting appears to be the best formulation of the problem studied so far. Three criteria are used to distinguish feasible districts:

1. The population of a district may not deviate from the mean district population by more than a given amount. This is expressed as:

   $$\left| p(j) - \bar{p} \right| \leq \alpha\bar{p}$$

   where $p(j)$ = the population of district j

   $\bar{p}$ = the average district population

   α = a number between 0 and 1 such that 100 is the maximum allowable percentage deviation of the population from the average district population.

2. Districts must be contiguous.

3. Compactness is measured in two ways:
   By distance which requires that two population units cannot be in the same district if the distance between their centers of (i,k) is greater than an exclusion distance $e(i,k)$
   Shape compactness is a dimensionless measure expressed as:

   $$C_j = d^2_j / A(j)$$

   $$C_j \leq \beta$$

   where d_j = the maximum $d(i,k)$ in district j $A(j)$ = the area of district j

   $0 \leq \beta \leq \infty$

The degree of compactness increases as d_j increases. With population equity, contiguity and compactness as criteria, Phase I implicitly enumerates all feasible districts from population units that satisfy the above criteria. Districts generated in Phase I are kept track of in a matrix, A. The matrix is S x N, where S equals the number of districts generated and N equals the number of population units. Each element in the matrix, a_{ij}, is either a zero or a one. If $a_j = 1$, then population unit i is included in trial district j.

The optimal districting plan is then calculated in Phase II in the following way:

$$\text{Min Max} \quad \sum_{j=1}^{s} C_j X_j$$

$$\text{Such that} \quad \sum_{j=1}^{s} a_{ij} X_j = 1 \qquad i = 1, \ldots\ldots N$$

$$\sum_{j=1}^{s} X_j = M$$

$$X_j = 0,1$$

where

X_j = 1 if district j is in a plan and 0 otherwise

N = number of population units

S = number of feasible legislative districts generated in phase I

$C_j = \left| P(j) - \bar{p} \right| / \alpha\bar{p}$

M = number of districts to be generated

Although this method will give an optimal solution there is still some human judgment needed to decide between the tradeoffs involved with changing the parameters. The two phase algorithm has been applied by Garfinkel and Nemhauser to several real problems using an IBM 7094. The algorithm was able to solve problems with fewer than 40 population units within ten minutes of computation time, but the algorithm was unable to solve a 55 population unit problem with an hour of computer time. The authors concluded that both computation time and the storage become critical when the number of population units is 50 or more, but with more funds and high speed external storage devices these problems will be overcome. What is uncertain, though, is whether this method would ever be feasible for districting problems of a size that are several times as large as a 50 population unit problem. Brookline, for example, has over 400 if blocks are used. (See Figure 5.3)

There have been other applications of districting algorithms to the analysis of municipal systems. For example, Heller, Markland, and Brockelmeyer (56) used districting to design police patrol beats for St. Louis, attempting to equalize workload and generate compact regions to minimize response time. However, Larson and Stevenson (71,72) have shown that an optimal districting plan for emergency services would not reduce response time greatly in comparison to a purely random allocation of emergency units.

The reasons for choosing the IOWA system over other heuristics such as REDIST are not overwhelming, but may be significant to potential users. The two most important are probably that it is cheaper to run and very well documented. The documentation made it possible to revise the algorithm in minor ways without unreasonable effort. While it might be possible with great effort to design a package specifically for districting cities into solid waste collection areas, it seems much more reasonable to use an available package such as the IOWA system and modify it slightly as necessary. The solution will not be optimal, and will probably have to be revised in the field, but the same can be said for any other feasible system. The only reasonable alternative is to use the intuition available in the specific case, which might be superior to the algorithm in some cases. However, such intuition is very dependent on the specific people involved. A districting routine which gives reasonable results at the worst will be useful as a standard procedure. It seems likely that the modified IOWA Redistricting System will meet this criterion.

5.3 Districting Results Using the Iowa Algorithm on Block Data

The districting algorithm produces plans with reasonably compact districts and small mean workload variance. It does this at low cost, but since its data base is block statistics, and the trucks actually collect street segments, a certain amount of revision must be done before routing. The time required for these revisions decreases the flexibility of using the system. Problems occur for two reasons: first, because some street segments are assigned to blocks in different districts; and second, because the blocks themselves are not compact.

It has proven to be fairly easy to generate plans with an acceptable mean workload variance. In all cases, the largest district is less than 20% bigger than the smallest; for most plans this figure is about 15%. This would mean that the smallest district of the

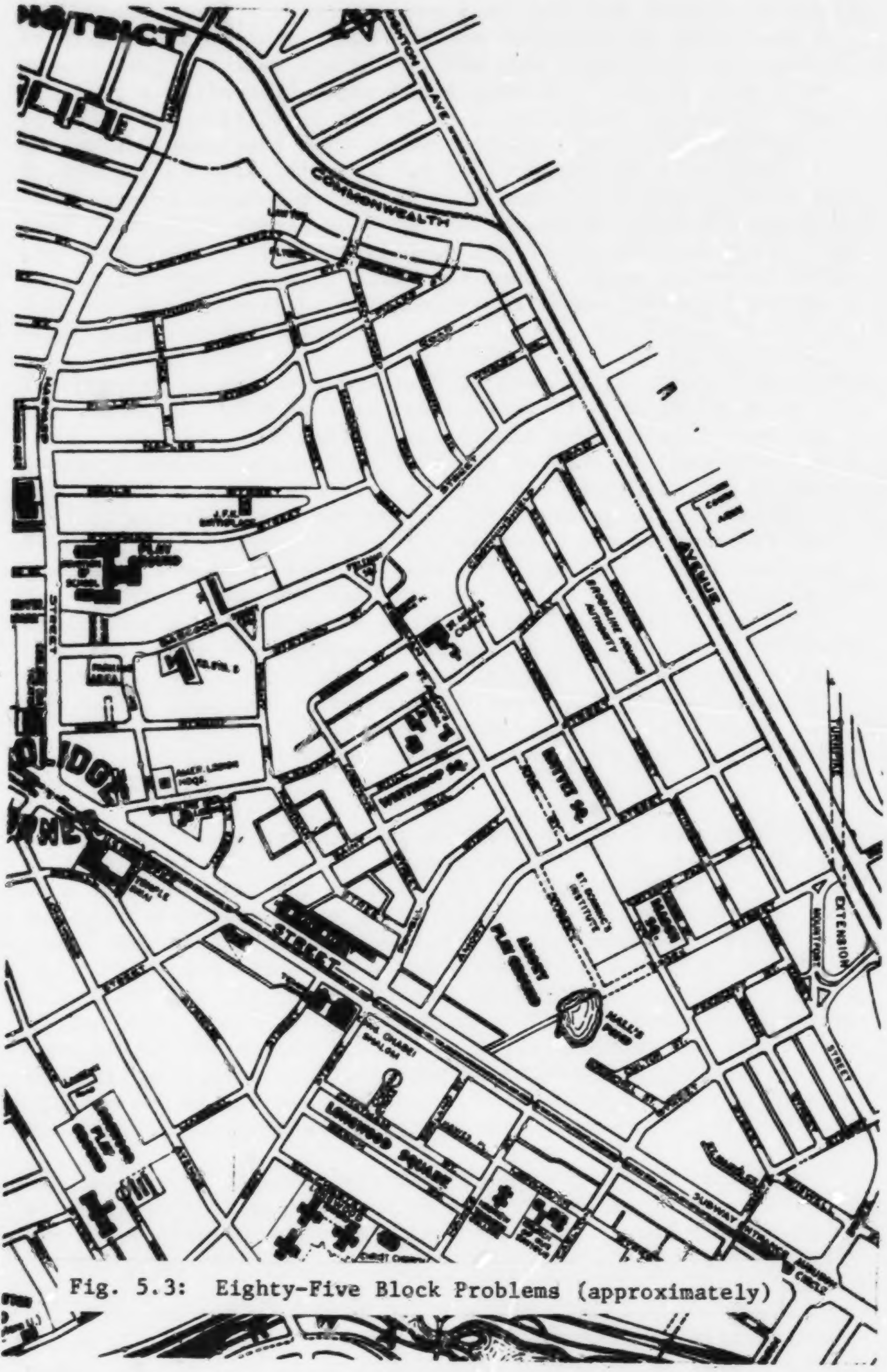

DISTRICT
COMMONWEALTH
AVENUE
STREET
LONGWOOD SQUARE
EXTENSION
STREET
STREET

Fig. 5.3: Eighty-Five Block Problems (approximately)

week would require about an hour less than the largest, assuming an eight hour maximum. The average deviation is about 2.5% or 10 minutes, for most plans. In the plan diagrammed on figures 5.4-5.6, a maximum of eight hours gave districts ranging from 6¾ hours up, with 37 of the 40 districts under 7½ hours. The median and mean were both approximately 7 hours, 10 minutes. In another example (figures 5.7-5.9) the smallest required 7 hours, the largest 8, and 34 were under 7½ hours. The standard deviation in this case was 14.5 minutes. In both examples, the distribution of the variances was skewed to give a few high values and many slightly below the mean. These values of workload variance should be acceptable, although further improvements might be possible.

The program is not as successful in generating compact districts. One reason for this is that the network it sees is based on the block centroids, and many of the blocks have unusual (and non compact) shapes (e.g. block 1-210 or 6-208). A long thin block may be added to the district so that the centroids are compact, but the actual street network of the district is not, as in district 29 in figure 5.5. This weakness can be remedied in the early stages of routing when efficient boundaries are made for the districts, but only at the cost of extra time and labor. In all but a few cases the plots of the block centroids are compact, and a few noncompact districts are probably unavoidable. Districts 23, 28, and 35 on map 6 and districts 20 and 38 on figure 5.9 fall into this category. It is possible, though, to revise a partially acceptable plan using the algorithm so that unacceptable districts could be improved with only a minimum of effort.

The districting program operates very well with the data available to it. Collection trucks, though, collect from the street segments of a district, not the blocks. Block data includes information on wasteloads from parts of three or four street segments. If block face data were available, or if the system collected only one site of the street at a time, the situation would be improved significantly. Compactness would be meaningful since the shape of the block would not be important. The process of modifying the boundary of the district would be mostly eliminated, since the boundary streets would no longer be covered by collection of both of the blocks between them. This would remove the slowest and least accurate phase of the process, increasing flexibility.

One feature of the districting procedure has only been used slightly to this point: the ability to easily generate districts for a specific subsector of the community. A curbside collection system must have fixed daily boundaries, which would preferably run along natural lines such as major streets. These boundaries could be set up from a full 40-district plan for the nominal collection problem. It would then be possible to also design plans for the five daily areas using a smaller or larger number

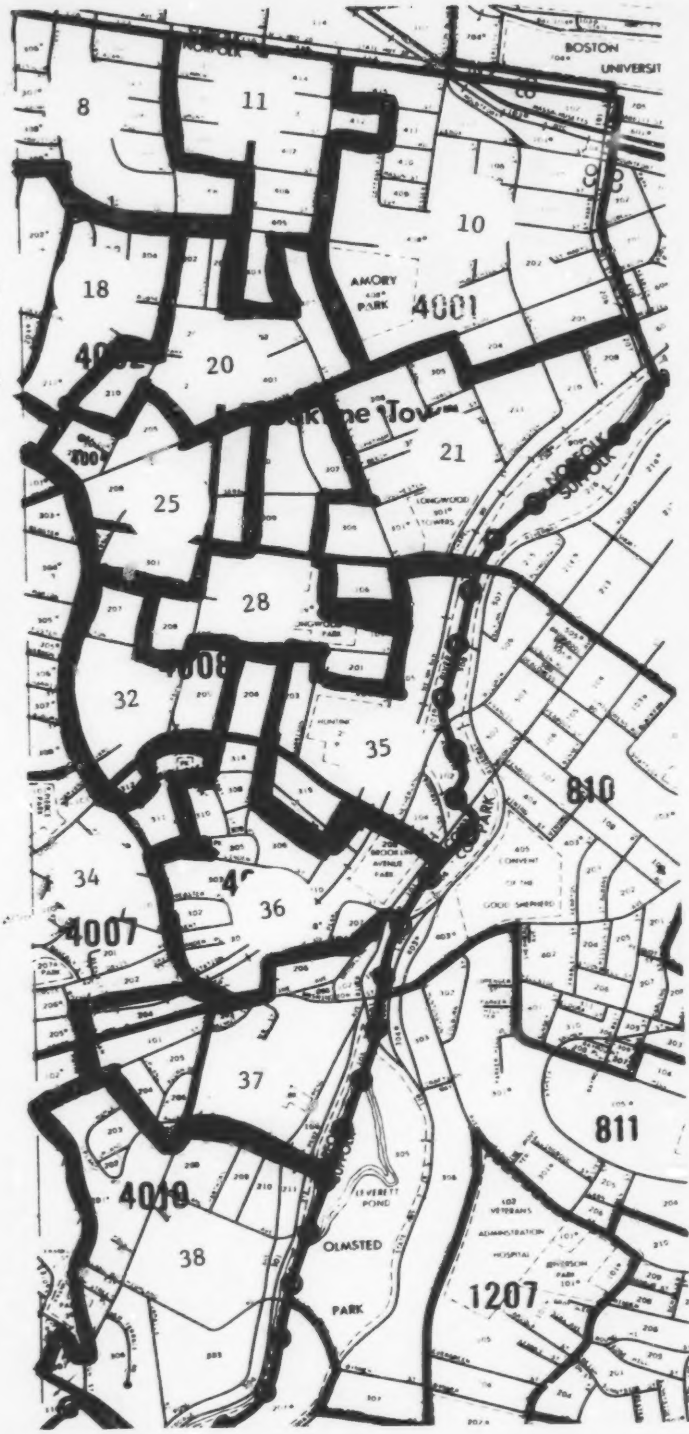

BOSTON UNIVERSITY
8
11
10
18
20
4001
4002
AMORY PARK
Brookline Town
21
LONGWOOD TOWERS
25
28
32
4008
35
810
34
36
4007
CONVENT OF THE GOOD SHEPHERD
37
811
4010
38
LEVERETT POND
OLMSTED PARK
VETERANS ADMINISTRATION HOSPITAL
1207

Figure 5.4 : Districting Plan A on Census Block Maps - North

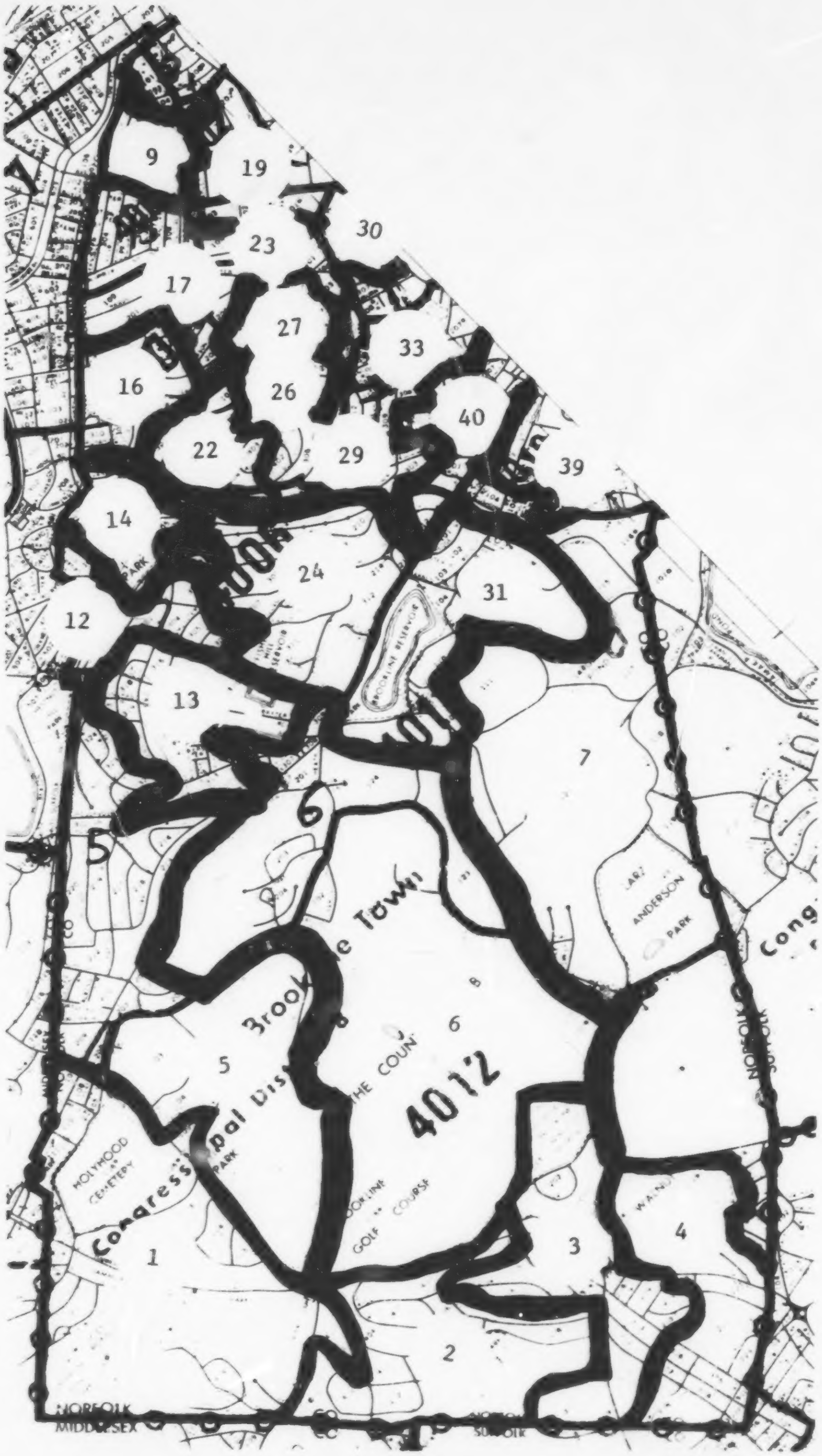

9
19
30
23
17
27
33
16
26
40
22
29
39
14
24
31
12
13
7
6
5
Brookline Town
Congressional District
4012
HOLYHOOD CEMETERY
LARZ ANDERSON PARK
BROOKLINE RESERVOIR
BROOKLINE GOLF COURSE
THE COUNTRY
PARK
1
2
3
4
5
6
8
NORFOLK
MIDDLESEX
NORFOLK
SUFFOLK
Cong

Figure 5.5: Districting Plan A on Census Maps - South

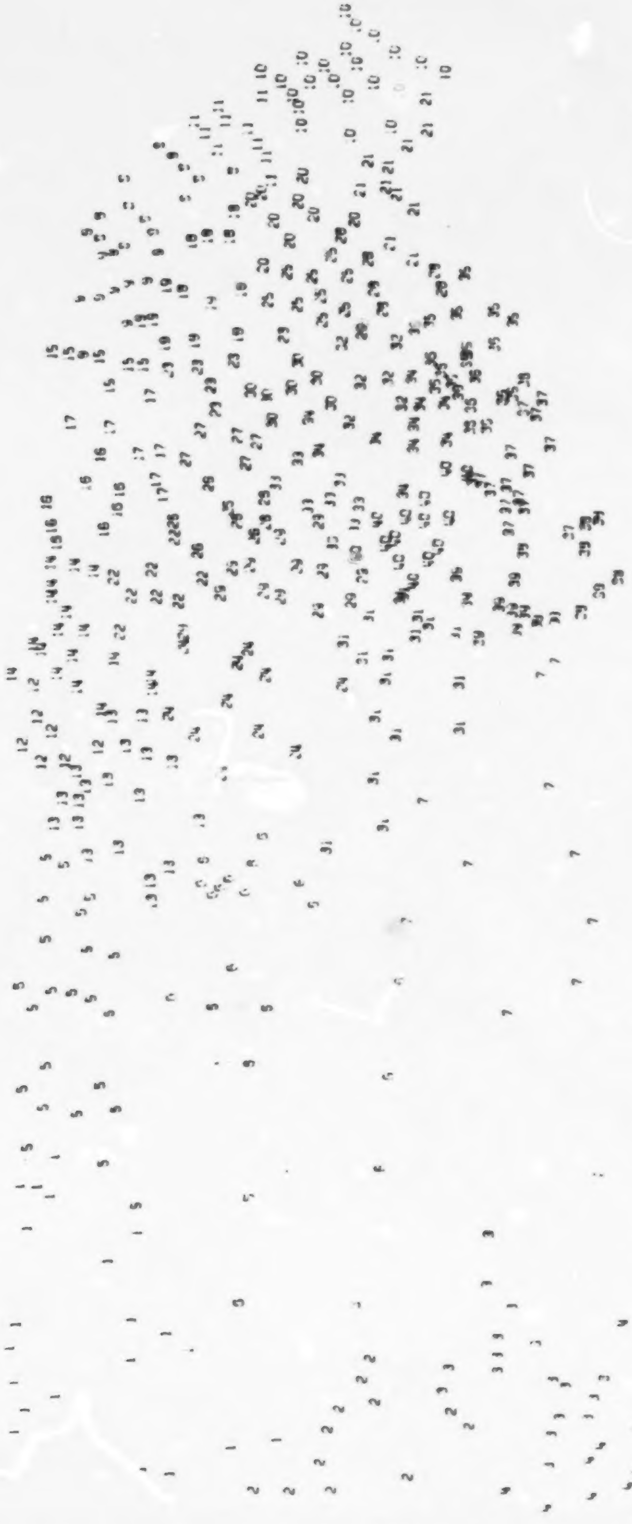


Figure 5.6: Plot of Districting Plan A

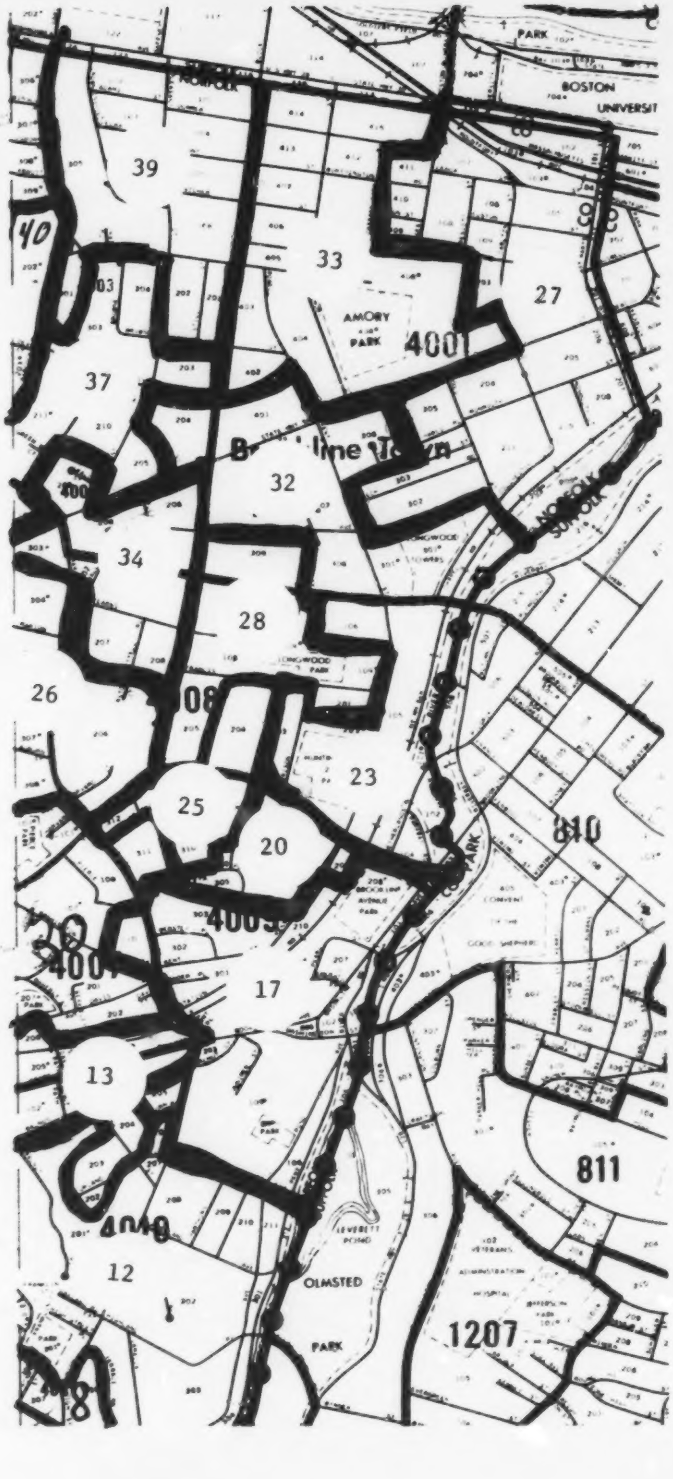

PARK
BOSTON
BOSTON UNIVERSITY
NORFOLK
39
40
33
27
AMORY PARK
4001
37
Brookline Town
32
34
28
LONGWOOD PARK
26
4008
25
23
20
810
BROOKLINE AVENUE PARK
CONVENT OF THE GOOD SHEPHERD
4005
30
4007
17
13
811
4010
12
LEVERETT POND
OLMSTED
PARK
VETERANS ADMINISTRATION HOSPITAL
1207
NORFOLK
SUFFOLK

Figure 5.7 : Districting Plan B on Census Maps - North

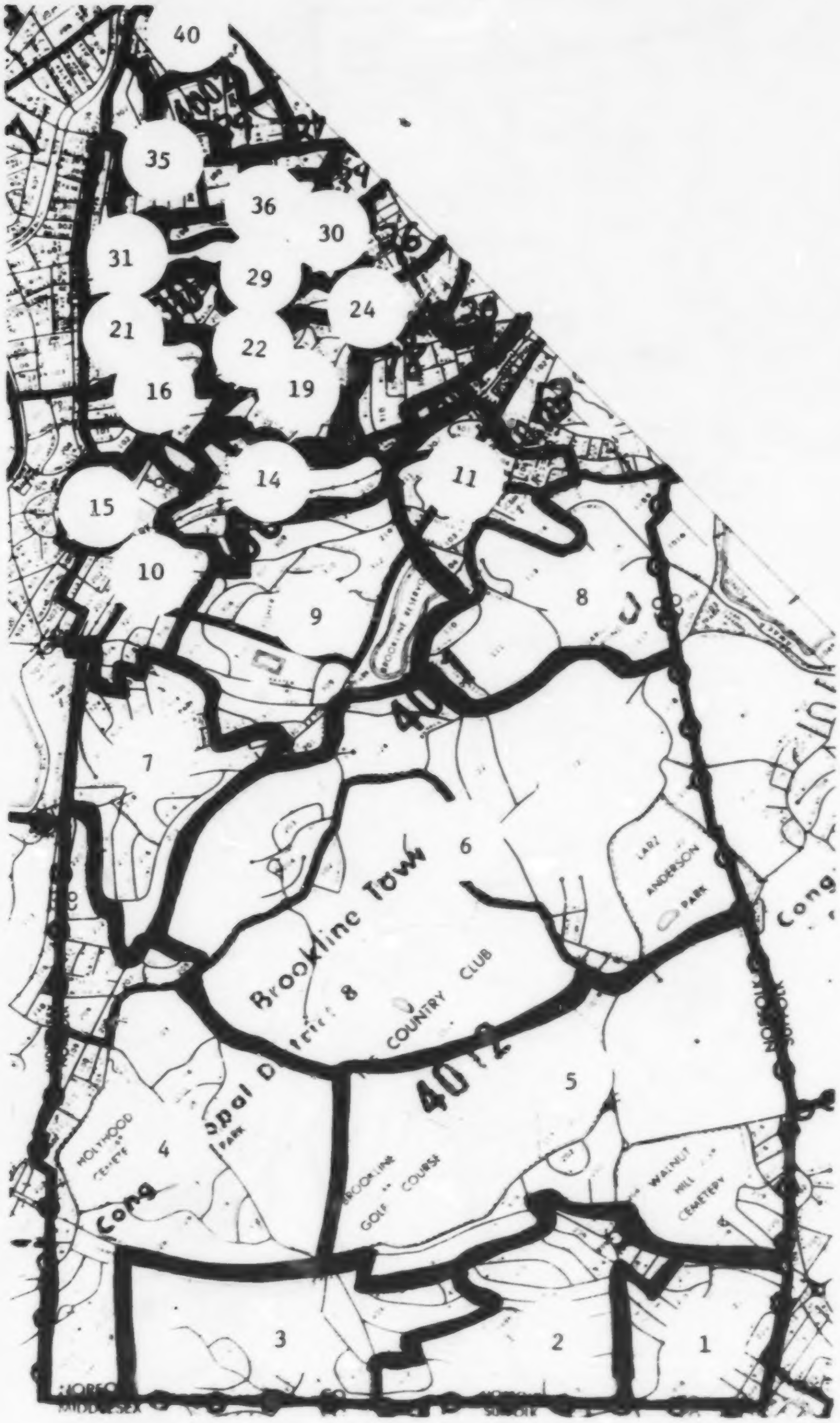

40
35
36
30
31
29
24
21
22
19
16
14
11
15
10
8
9
40
7
6
LARZ ANDERSON PARK
Brookline Town
District 8
COUNTRY CLUB
Cong
402
5
HOLYHOOD CEMETERY
4
Cong
BROOKLINE GOLF COURSE
WALNUT HILL CEMETERY
3
2
1
NORFOLK SUFFOLK
NORFOLK MIDDLESEX

Figure 5.8 : Districting Plan B on Census Maps - South

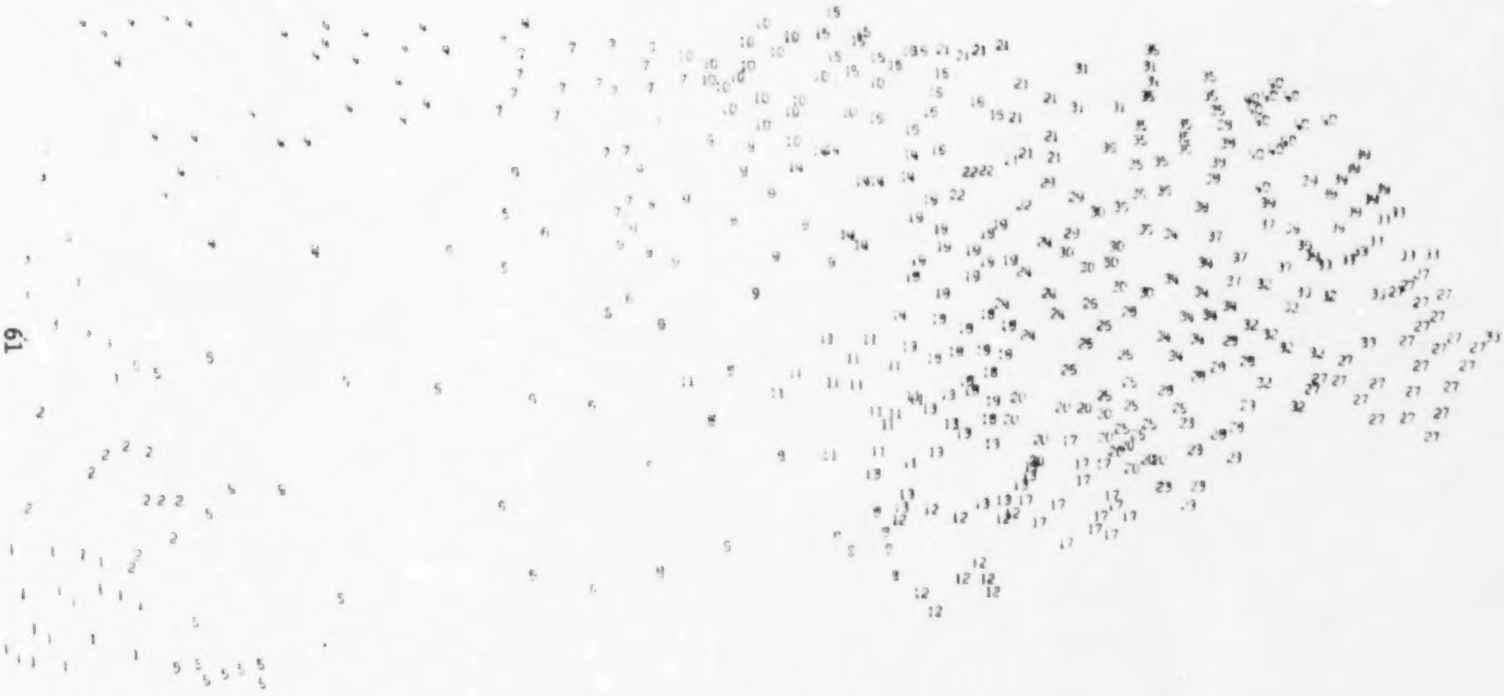


Figure 5.9 : Plot of Districting Plan B

of trucks, so that the managers would be able to efficiently route the trucks on heavy or light days.

The cost of using the algorithm is small. Data on the locations and contiguities of the small collection units can be found from a map. For the 463 locations and 22,000 contiguity cells of the sample Brookline problem, writing, keypunching and checking these lists took well under a man week (although it was a busy week). Block population and housing data can be found in published census reports, or off of the census tapes. These must of course be converted into expected collection times, as described in chapter 7. Running the algorithm is also inexpensive: a typical Brookline run might cost six dollars, (using an object deck) with a plot such as figure 5.6 added for two dollars more. Detailed block maps such as figures 5.4 and 5.5 can be drawn with minor effort.

The districting algorithm is effective and inexpensive, limited only by the data it requires. If data can be found which models the actual collection process, it will produce equitable districts which are compact and can be routed very simply. If not, the districts will still be equitable and reasonably compact, but they require some modification before routing. The workload variance will be small in either case, but it is similarly only as accurate as the data given it. The following section describes runs using street segment loads, as an alternative data base. For clarity, the work in Brookline is again cited.

5.4 Block Face Districting Results

The northeastern section of Brookline, bounded by Harvard Street and Longwood Avenue, and containing approximately one-fifth of the population, was coded using both block and street segment data, and districting runs done. Block data consisted of census block population placed at the block centroids. Segment data placed these populations along each face using *a priori* knowledge of the area. Errors were undoubtedly made in this process, but the experiment was done primarily to test the feasibility of using segment data, so such errors are unimportant. The main result was that districts generated using data based on street segments needed less revision than census block districts, and that revision was easier. However, some revision was still necessary and accurate data would be much more difficult to obtain.

The discussion of Euler tours and the Chinese Postman problem (Chapter 6) shows the importance of odd nodes. In districting, it is therefore crucial to create as few extra odd nodes as possible. A standard four-street intersection on a boundary should be divided into two streets per district instead of three-one. Since the districting program does not implicitly consider this problem, districts must be modified slightly to minimize the number of odd nodes. This is not trivial, since the populations must also be kept balanced. However, it is also not very difficult when data on the loads for each street segment are available.

The main change is that the whole process of deciding which district should collect a boundary street is removed. Figures 5.10-5.14 show three plans using block data. Since the data was more disaggregate for the segment runs (237 units vs. 91) the population variances are better: 1.03, 1.04, and 1.09 for the segment runs versus 1.17 and 1.11 for the block plans. Note that a 3% difference is less than 15 minutes expected time difference between routes given accurate data, and is easily satisfactory. Compactness is important only as a general guide; the routes are contiguous and reasonably compact. In many cases the basic district shape is the same for both types of plans, but the segment runs give lower population variances and much more usable results. Street segment or block face data should definitely be used if available. It is impossible, though, to give a general answer to the question of whether it is worthwhile to collect segment data instead of using available block data, since both the costs and the benefit depend on the particular situation. Districting runs with segment data are more expensive, and plots more difficult to produce, but these costs are minor. More important are the expected number of plans desired, the expected accuracy of the data from the various sources, and the resources available.

One option is to use block data for estimating waste loads, and simply assume that disaggregation to the segment level from these loads can be done in a reasonably unbiased manner. A time model could then be constructed for prediction and districts formed.

5.5 Linear Programming Districting Models

Two models for districting using linear programming techniques have been investigated. There are three major problems with these models: they require the choice of district centers; contiguity is not always required; and they can be relatively expensive to use. Their main advantages are simplicity, a reduction in data requirements (no contiguity list), and a greatly increased capacity for sensitivity analysis -- expecially on the important tradeoff between district compactness and workload equality. Figure 5.15 shows the minimum distance assignments for a small area in Brookline; Figure 5.16, the best results using the Helbig model; and Figure 5.17, the equal workload assignments

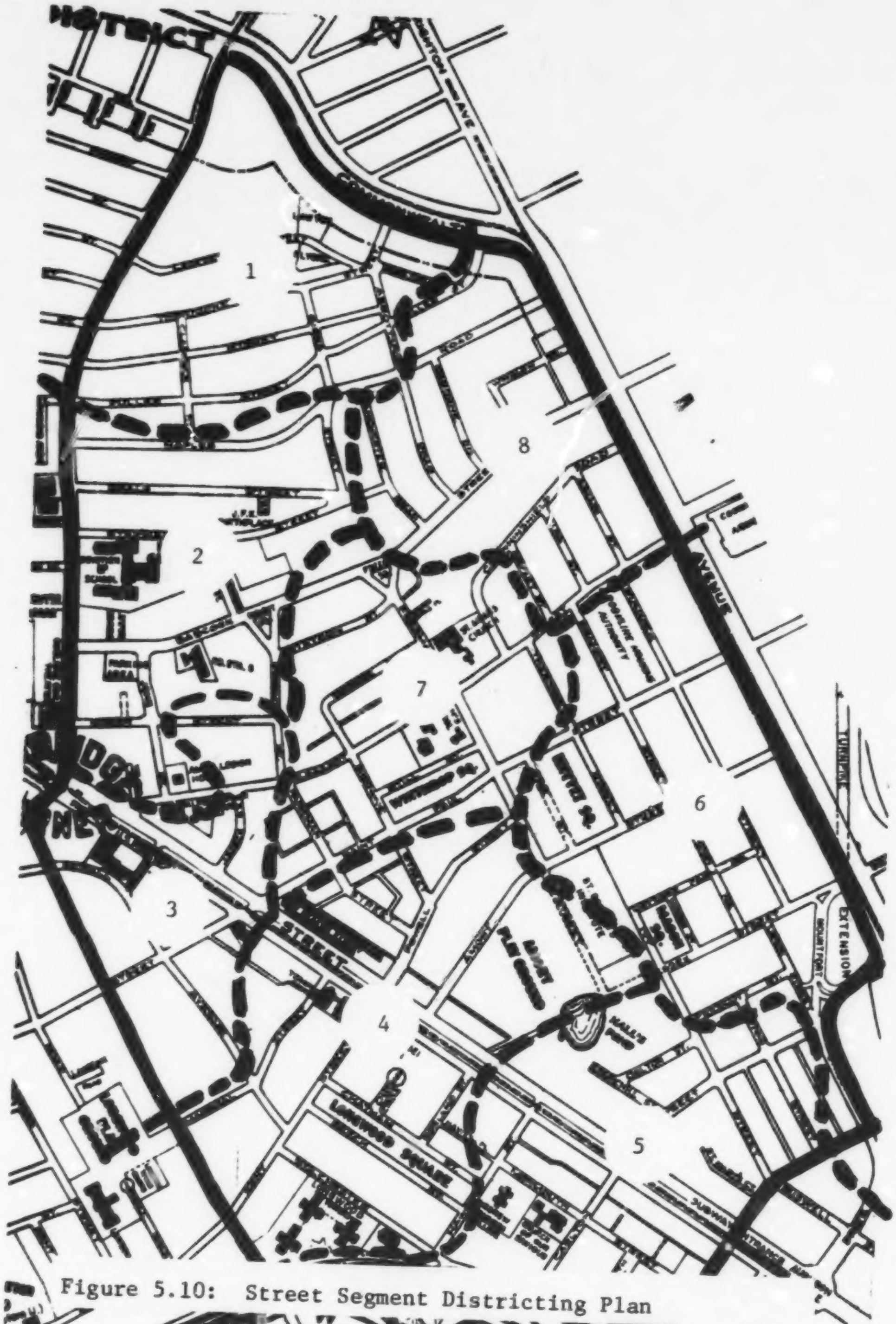

DISTRICT
COMMONWEALTH
AVENUE
1
8
2
7
6
3
STREET
4
5
LONGWOOD SQUARE
WINTHROP SQ.
HALL'S POND
EXTENSION

Figure 5.10: Street Segment Districting Plan

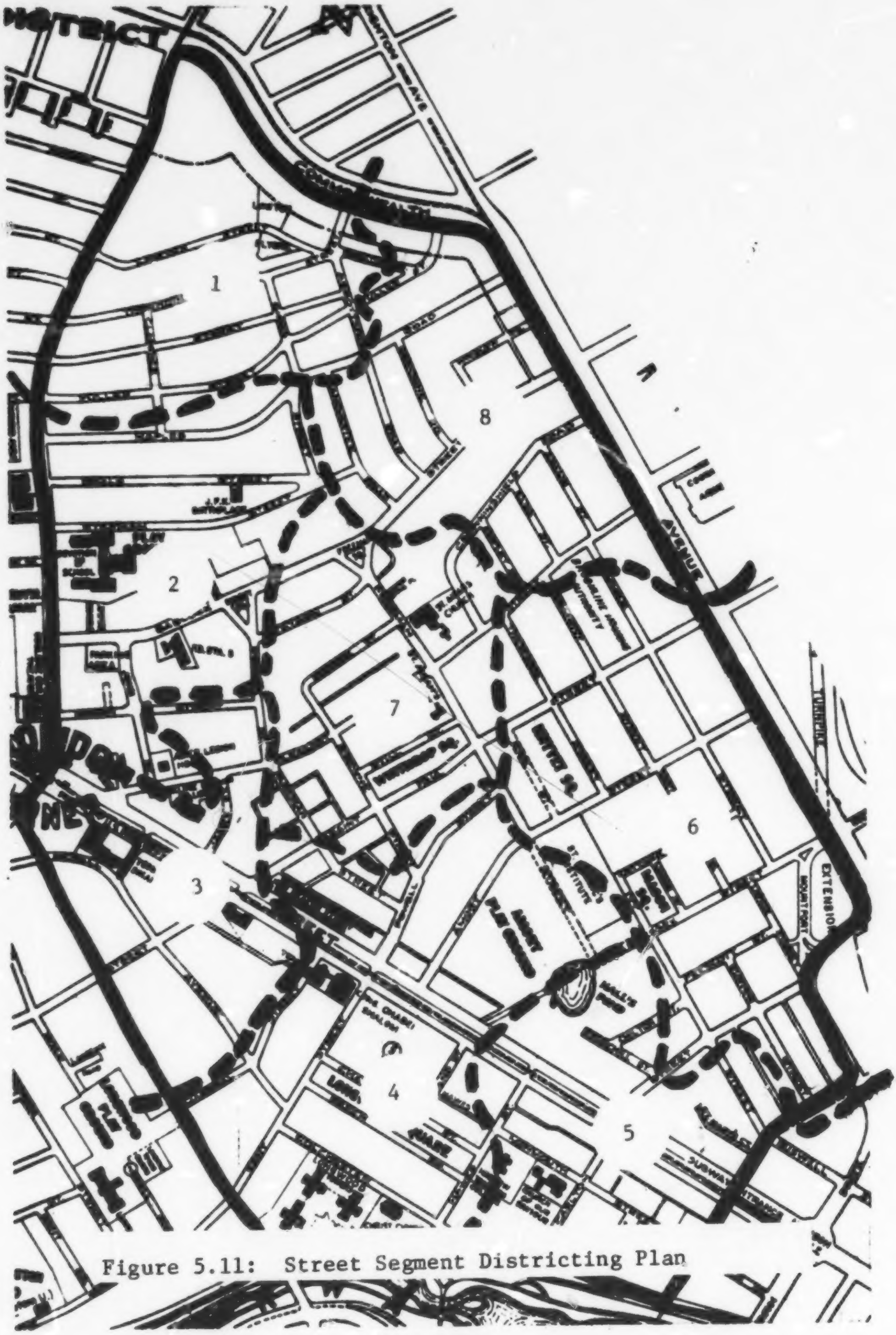
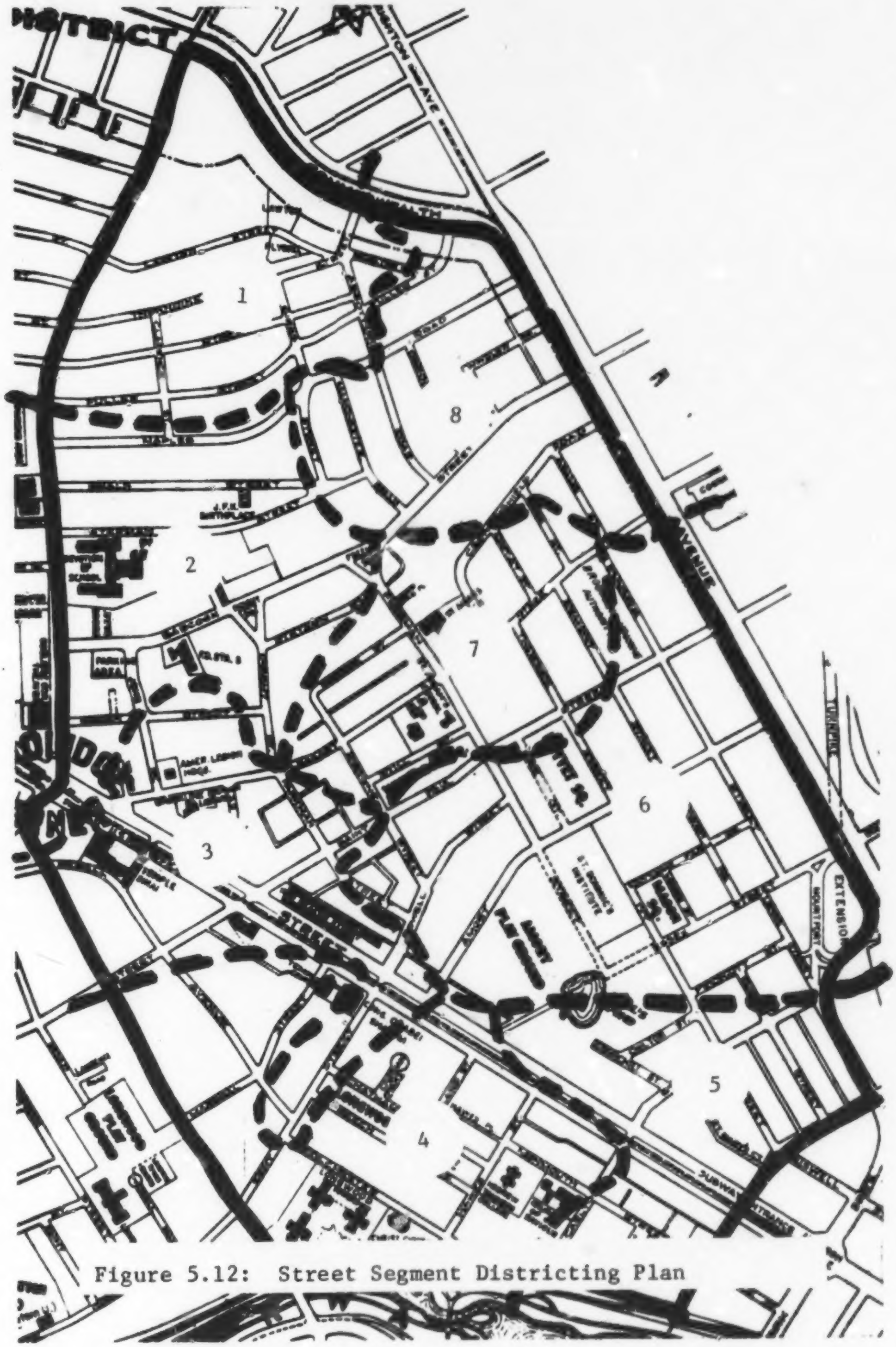

DISTRICT
COMMONWEALTH
AVENUE
1
8
2
7
6
3
4
5
EXTENSION

Figure 5.11: Street Segment Districting Plan


DISTRICT
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2
3
4
5
6
7
8
COMMONWEALTH
AVENUE
J.F.K. BIRTHPLACE
AMER. LEGION HDQS.
EXTENSION
MOUNTFORT
STREET
SUBWAY ENTRANCE

Figure 5.12: Street Segment Districting Plan

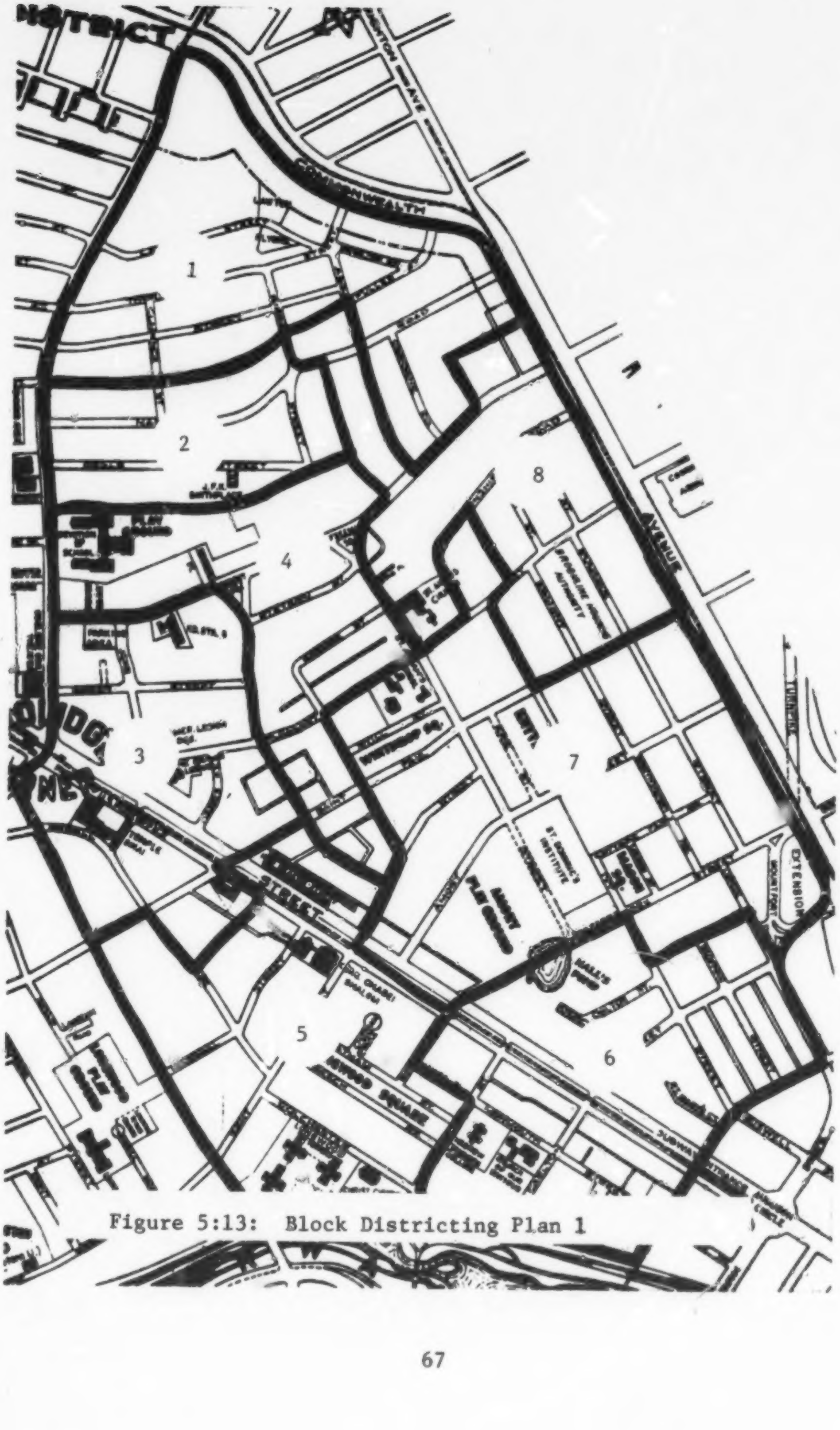

DISTRICT
COMMONWEALTH
AVENUE
1
2
3
4
5
6
7
8
WINTHROP SQ.
ST. DOMINIC'S INSTITUTE
STREET
HEYWOOD SQUARE
EXTENSION

Figure 5:13: Block Districting Plan 1

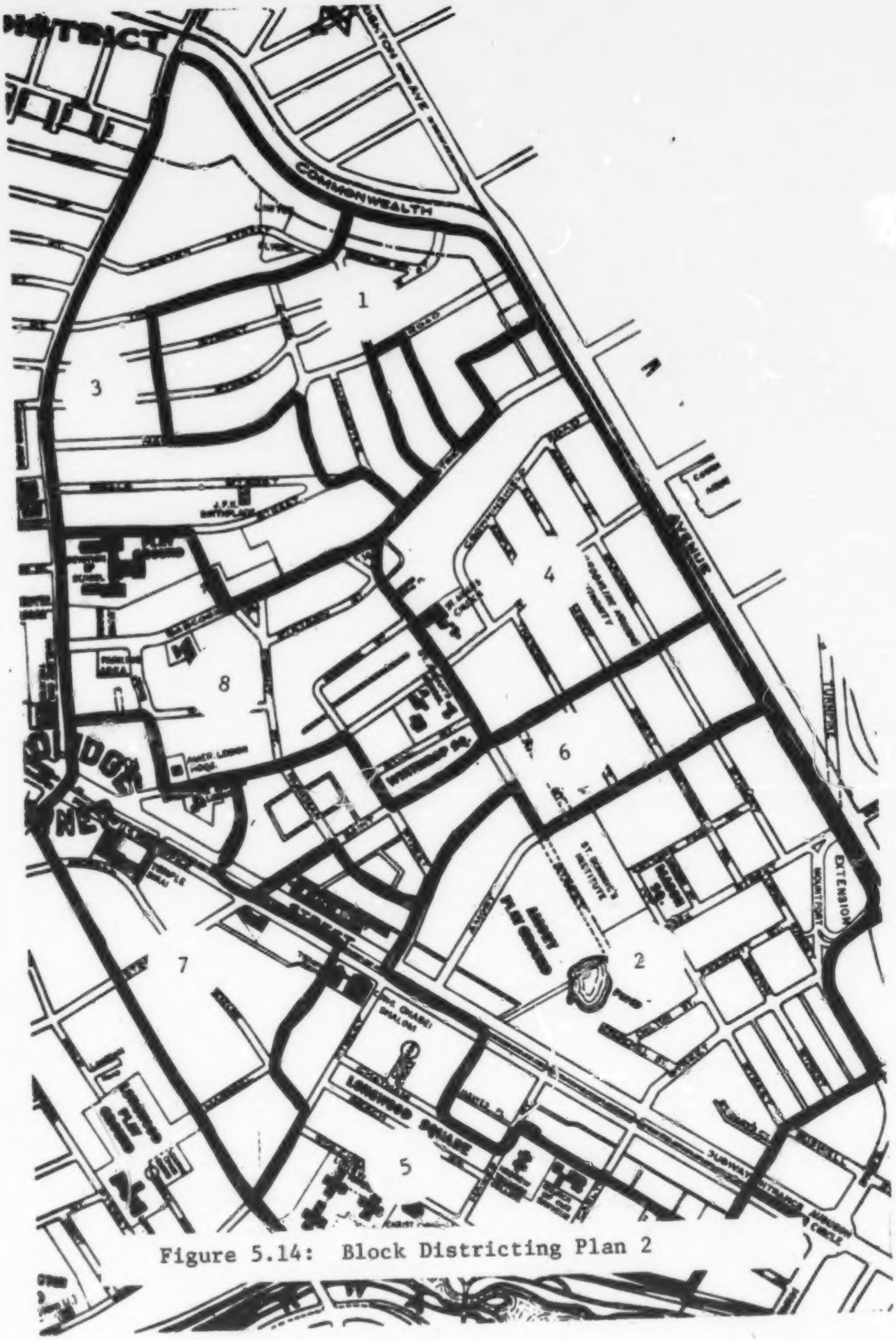

DISTRICT
COMMONWEALTH
AVENUE
J.F.K. BIRTHPLACE
WINTHROP SQ.
LONGWOOD SQUARE
EXTENSION
1
2
3
4
5
6
7
8

Figure 5.14: Block Districting Plan 2

using the Hudson model. Table 5.1 gives a set of district statistics for these runs.

There are significant possible uses for these models. They are simple, so it would be possible to produce a few sets of districts (e.g. figures 5.15 and 5.17) with little labor, and then modify these by hand to reach a good tradeoff between workload equality and compactness.

A technique has been developed called Generalized Upper Bounding (75), which makes it possible to greatly reduce the cost of solving such linear programming problems. Cost is basically an exponential function of the number of rows. GUB would reduce the effective number of rows for the full Brookline problem (463 blocks, 40 districts) from 550 to about 50, saving greatly in costs. The Helbig model can also be solved using network routines, which are much cheaper than full linear programming packages.

The plans developed compare well with those generated by the IOWA routine (e.g. figures 5.13 and 5.14), even without modifications in the choice of district centers. The Helbig algorithm is probably the simplest to implement in practice, although computer costs might be high.

It seems likely, however, that any of the districting heuristics could work effectively. If this is the case, then the choice should be done depending on the availability of the routines, the data required for them, and the cost of using them to generate districts

5.6 Rational Aggregation of Collection Districts

One important set of questions is that of how the collection districts should be aggregated into daily collection areas and weekly truck routes. The objectives for the daily collection areas are twofold: it should be easy to tell residents which district they are in, and it should be easy to supervise the crews. A measure for the former is the length of the area boundary; for the latter, a reasonable measure is the compactness or squareness of the area. Both of these are minimized in the political districting-type algorithms by their compactness measures. For the weekly truck routes, it seems best to make them as continuous as possible. If a crew finishes early one day, they might start on the next day's work (if, of course, the waste is available). If a crew runs late on a particular day, they may have to collect the remaining wastes in that district at the beginning of the following day. In either case, a continuous route enables them to do so without having to

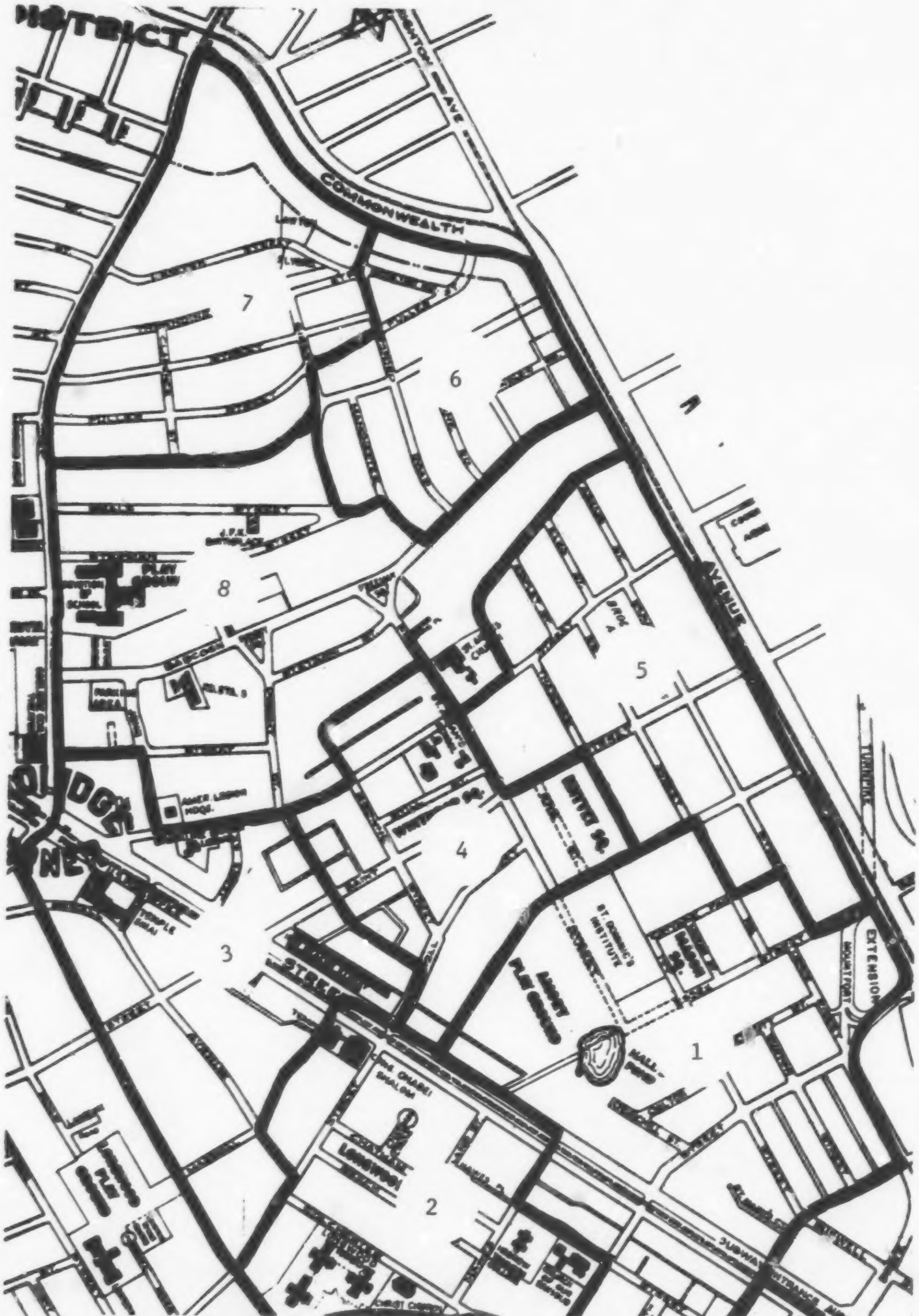

DISTRICT
COMMONWEALTH
AVENUE
7
6
8
5
4
3
2
1
STREET
ST. DOMINIC'S INSTITUTE
EXTENSION

Figure 5.15: Districts Under Minimum Distance Criterion.

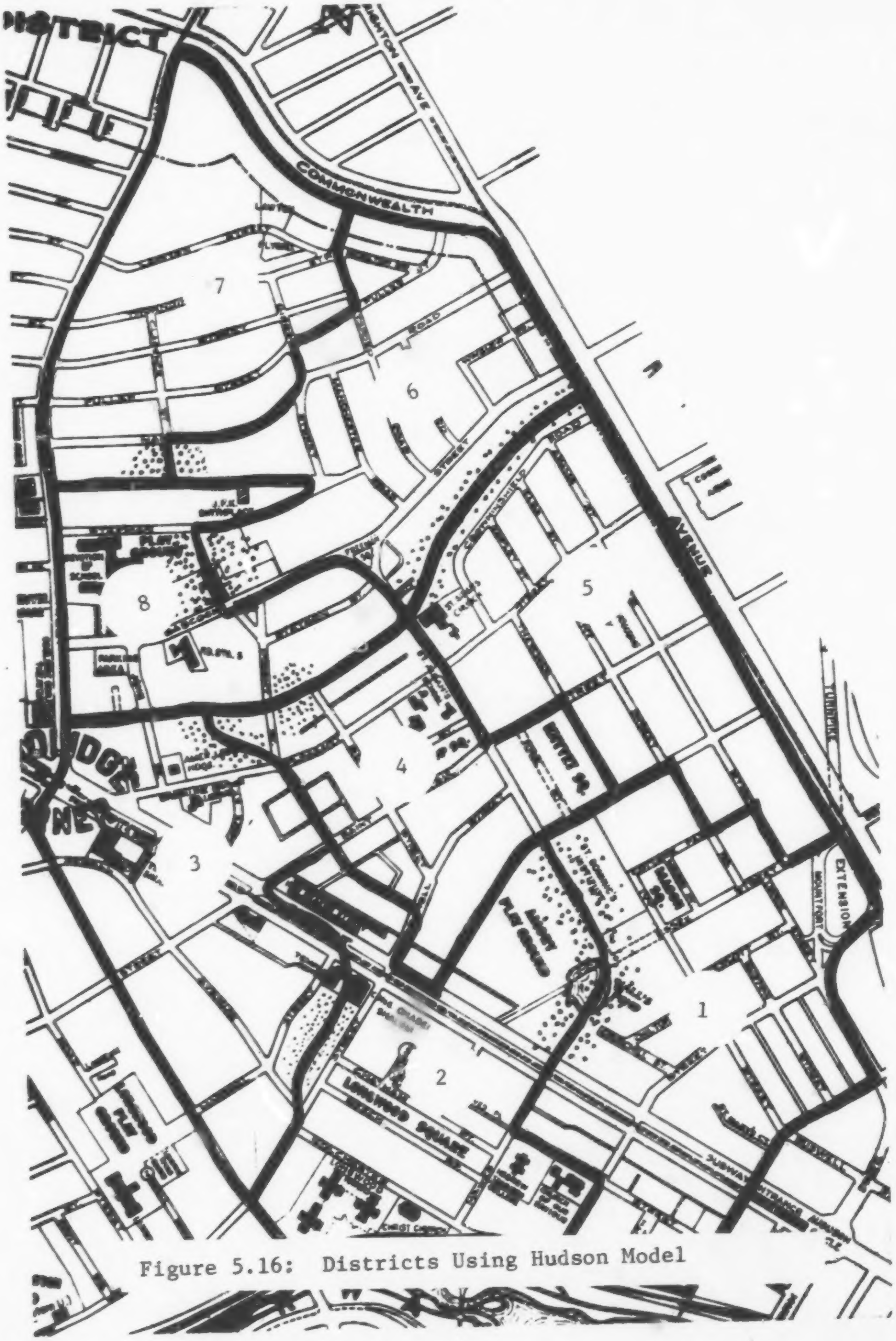

DISTRICT
COMMONWEALTH
AVENUE
EXTENSION
LONGWOOD SQUARE
7
6
8
5
4
3
1
2

Figure 5.16: Districts Using Hudson Model

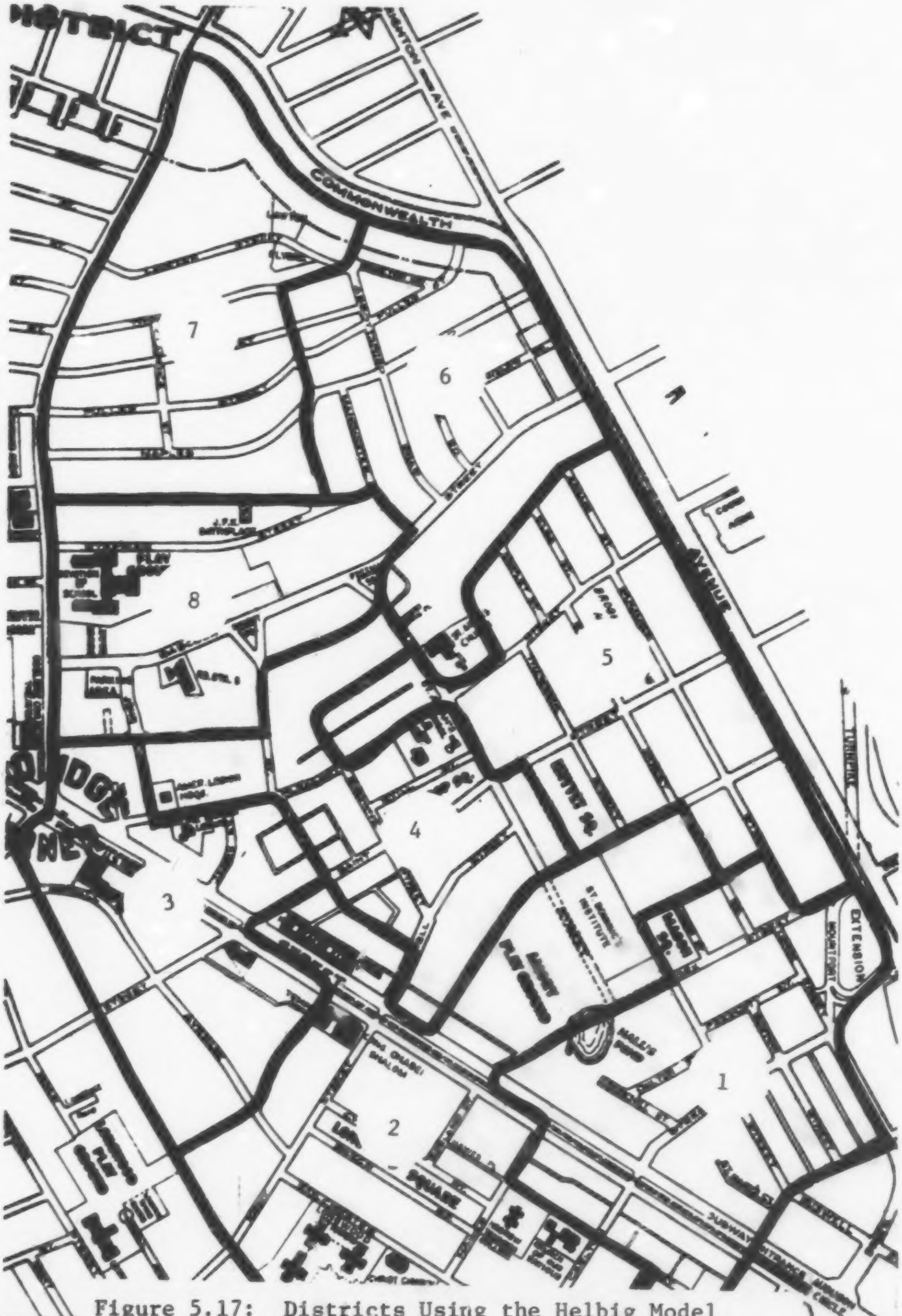

DISTRICT
COMMONWEALTH
AVENUE
EXTENSION
TURNPIKE
7
6
8
5
4
3
1
2

Figure 5.17: Districts Using the Helbig Model

I. Distance objective only (Figure 5.15) Z = 744.29

District	G_j	P_j
1	23	17521
2	8	7195
3	12	15913
4	9	10270
5	11	12214
6	9	9423
7	10	12636
8	9	25764

II. Workload Equality (Figure 5.16) Z = 773.16

1	21.31	13867
2	12.53	13867
3	9.53	13867
4	10.36	13867
5	13.49	13867
6	10.28	13867
7	10.36	13867
8	5.13	13867

III. Best Plan (Figure 5.17) Z = 775.08
using the Helbig algorithm

1	21	13168
2	12	12811
3	10	14650
4	9	14773
5	15	12975
6	12	14534
7	9	14377
8	5	13648

Table 5.1: Segment Districting Comparisons

travel extra distance (see figures 5.18 and 5.19).

Once the daily areas are chosen, it is possible to assign the weekly truck routes by either maximizing the number of directly connected districts using dynamic programming or first computing the minimal distance allocation between each pair of days using a transportation code and then using dynamic programming to choose the best overall flow. In either case, it is first necessary to measure the efficiency of having one daily area followed by another. A simple measure is just a count of the number of district touches: if three districts in area i are contiguous to districts in area j, and area j is assigned to the day after area i, it is possible for three of the trucks to have continuous routes. A slightly more complex measure of wasted time is the minimum distance which must be traveled if all trucks are late in area i and must travel to districts in area j. This can be found using a simple transportation code. Under both measures, a matrix is generated showing the gain (or cost) of having each area followed by each other. It is then a fairly simple process to order the daily areas to maximize continuity or minimize waste distance. This leads to optimal weekly truck routes for the set of daily areas.

The aggregation methods shows a great deal of insensitivity to the particular districting plan used. It appears that only a small number of satisfactory sets of daily areas exist for any plan, so that there are only a few degrees of freedom available in designing weekly routes. In Figures 5.20-5.23, a single plan is aggregated into four different sets of compact daily areas. The results of the optimal weekly route allocations are shown in Table 5.2. They suggest that planned assignments of crews to districts can save a certain amount of time, but that this amount is limited by the compactness of the daily collection areas. Similar results are shown for both of the measures of effectiveness.

To the extent that the aggregation problem described above is a real problem, it can be solved well. It is not clear, though, that the problem is a real one: it seems likely that the sort of hybrid between weekly and daily route systems assumed is actually uncommon. Even, for systems which work in that manner, it might be more desirable to attempt to equalize workloads over the week, rather than through individual daily districting. Seniority might also control weekly route choice. The problem of designing daily collection areas and weekly truck routes is not a trivial one. It seems likely that the daily areas should use "natural boundaries" as much as possible, and no good techniques have been developed for this. The weekly routes for the trucks may depend on seniority, or on equalizing work, or on the "between-days" efficiency described, or on some other measure. The clearest thing that can be said is that daily areas and weekly routes should be chosen rationally, with some set of explicit goals.

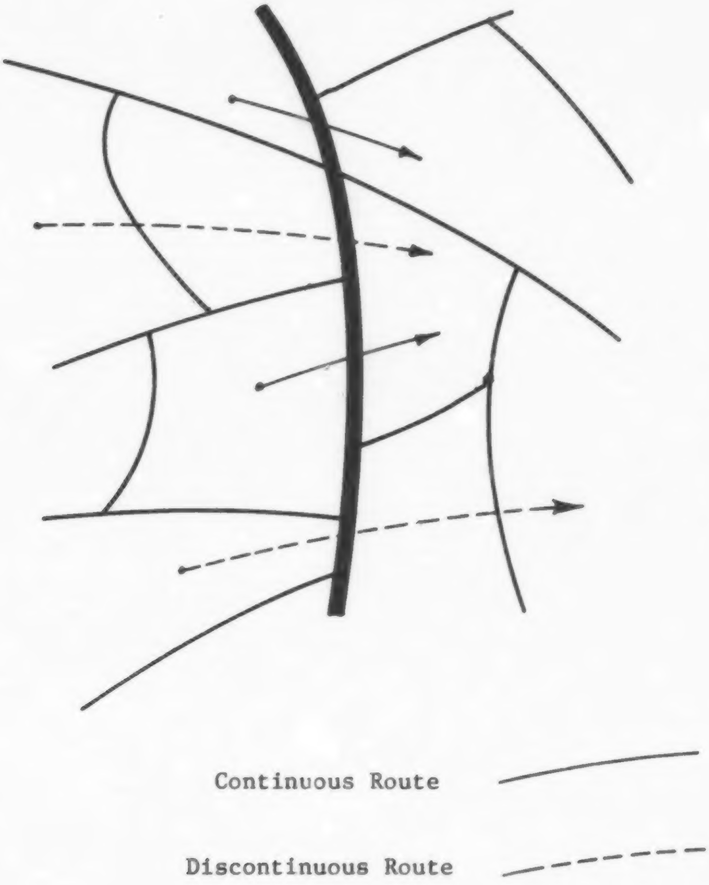
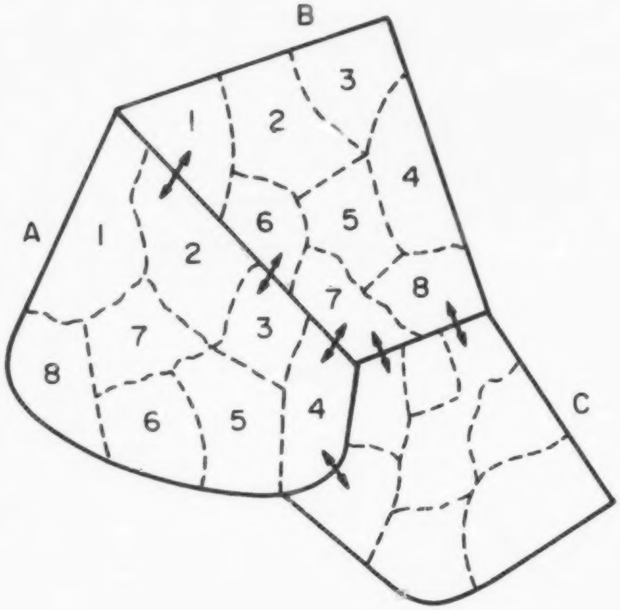

Continuous Route
Discontinuous Route

Figure 5.18: Truck Continuity Between Days



Continuous Route

3 continuous routes between day A and day B
2 continuous routes between day B and day C
1 continuous route between day A and day C

Optimal order of days is A-B-C with five continuous routes

Figure 5.19: Sample Collection Ordering

Optimal: 11 Continuous Routes *or* distance cost of 1739.57

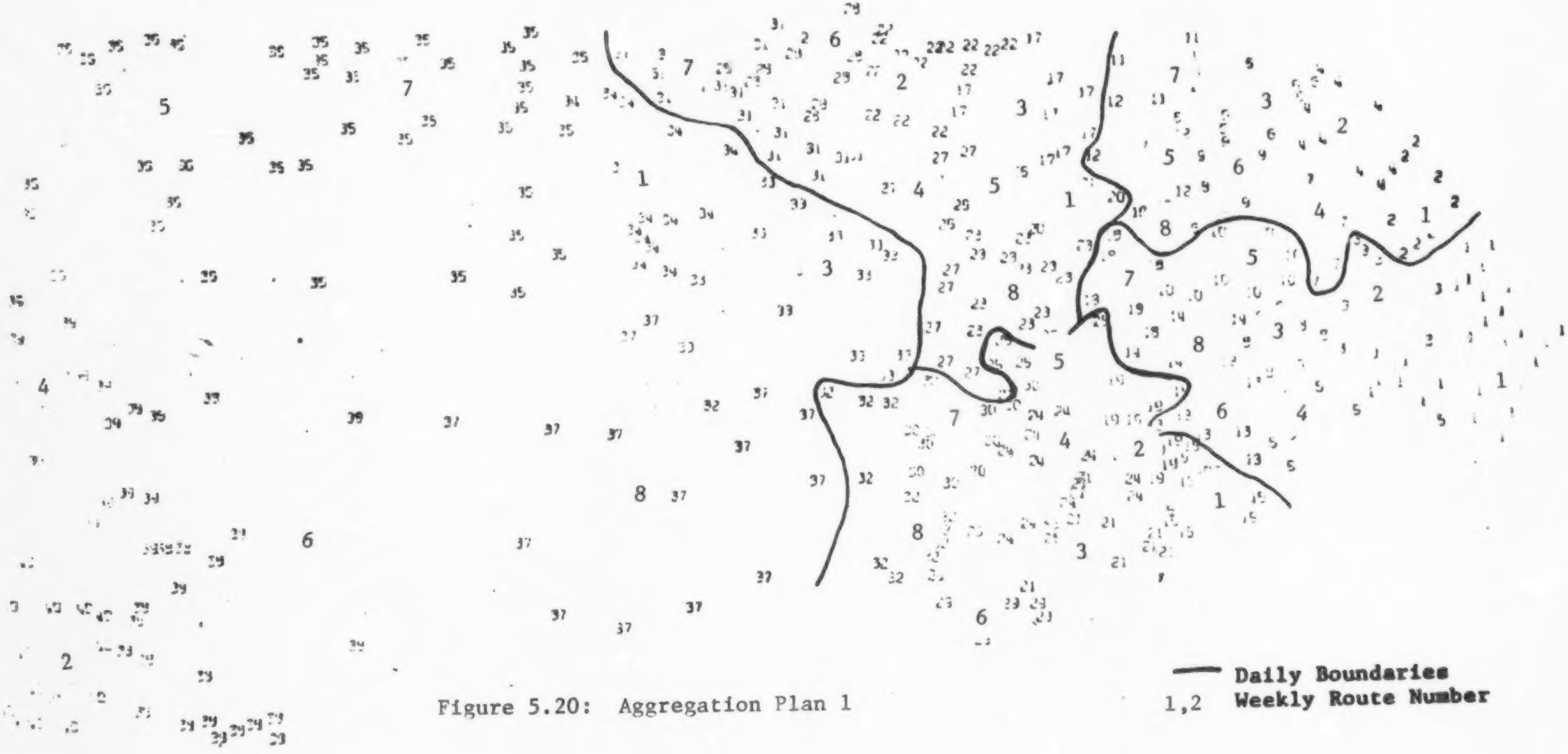

Daily Boundaries
1,2 Weekly Route Number

Figure 5.20: Aggregation Plan 1

Optimal: 14 continuous routes or distance cost 1436.0

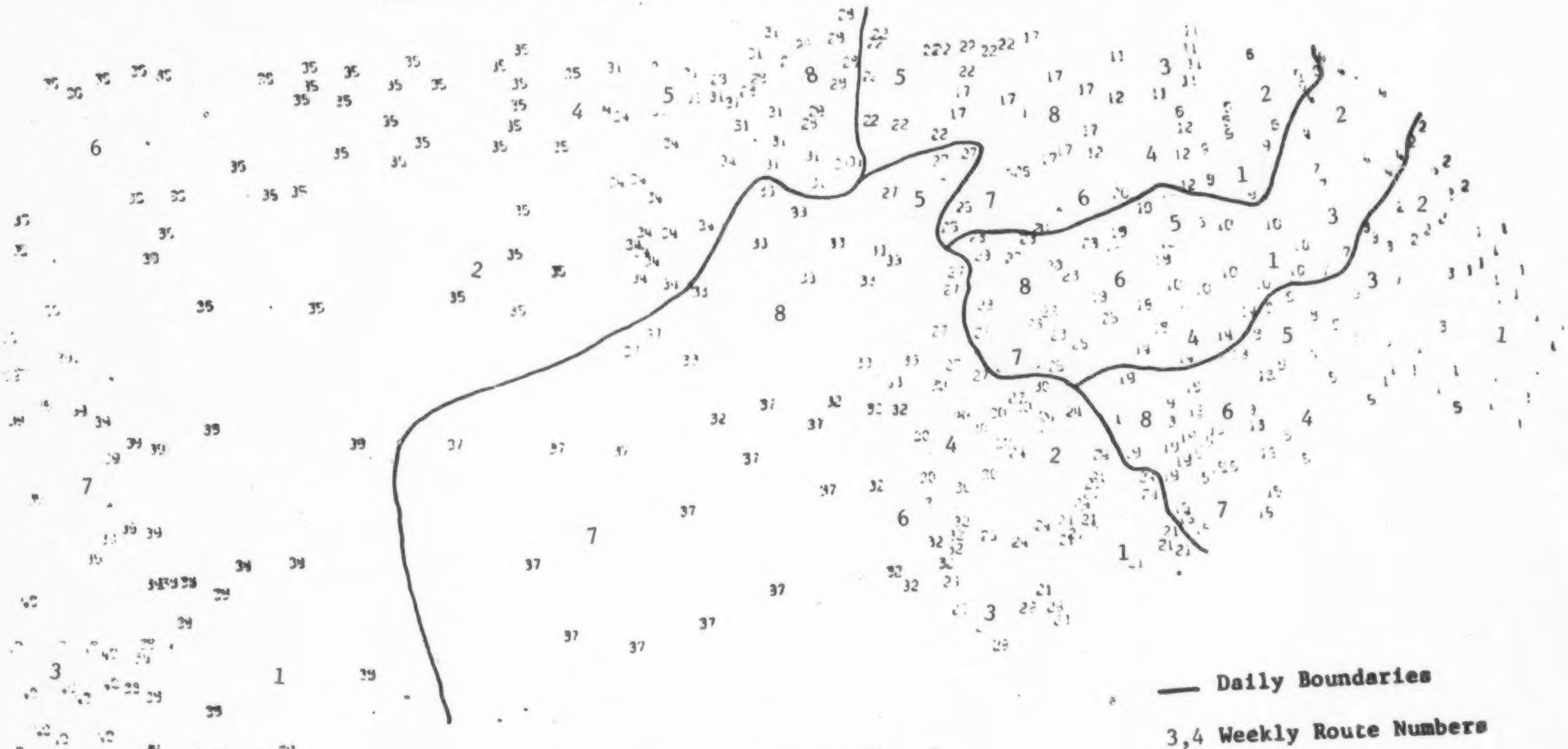

— Daily Boundaries
3,4 Weekly Route Numbers

Figure 5.21: Aggregation Plan 2

Optimal: 12 continuous routes or distance cost 1755.12

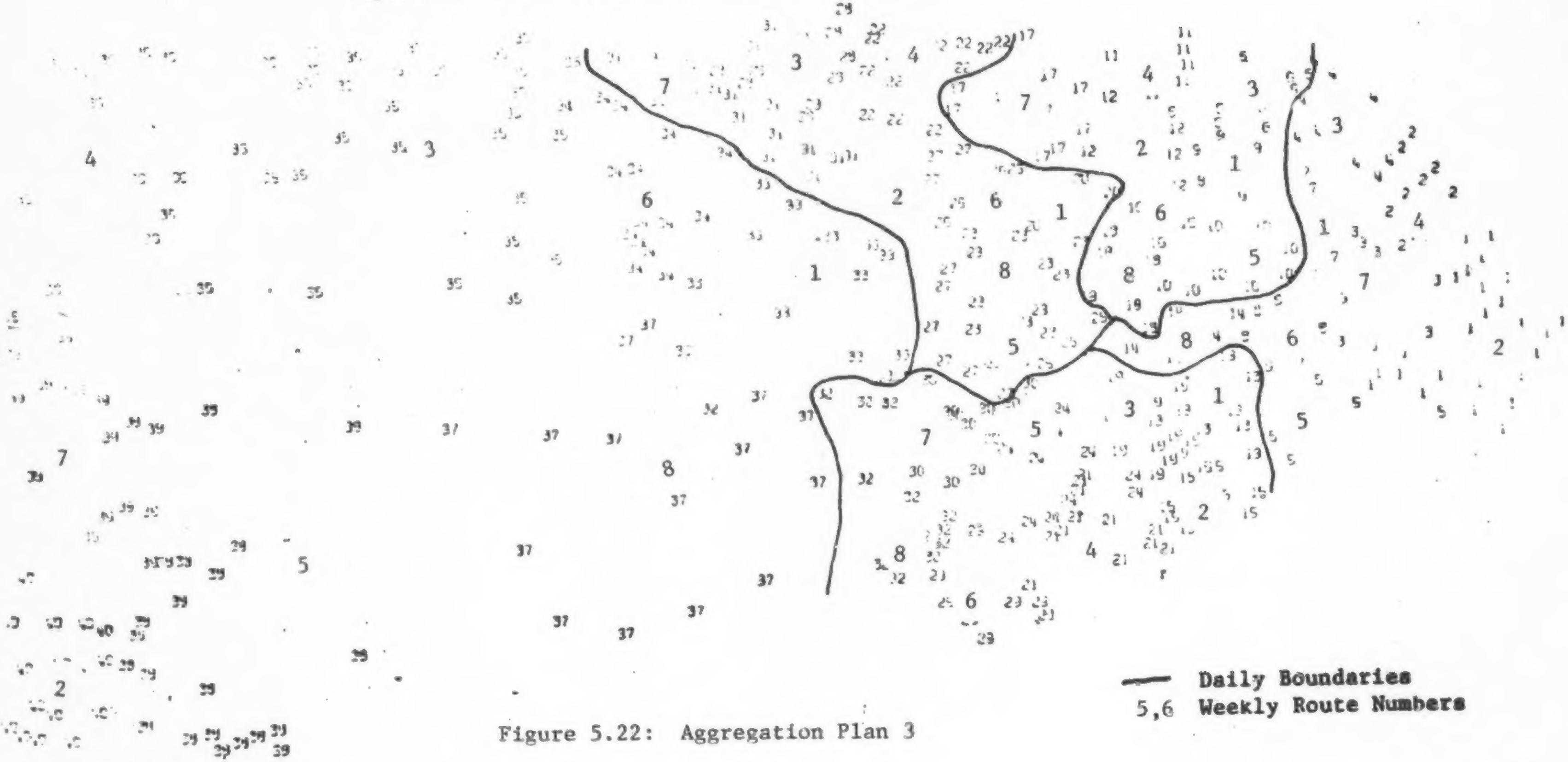

Daily Boundaries
5,6 Weekly Route Numbers

Figure 5.22: Aggregation Plan 3

Optimal: 14 Continuous routes *or* distance cost 1684.01

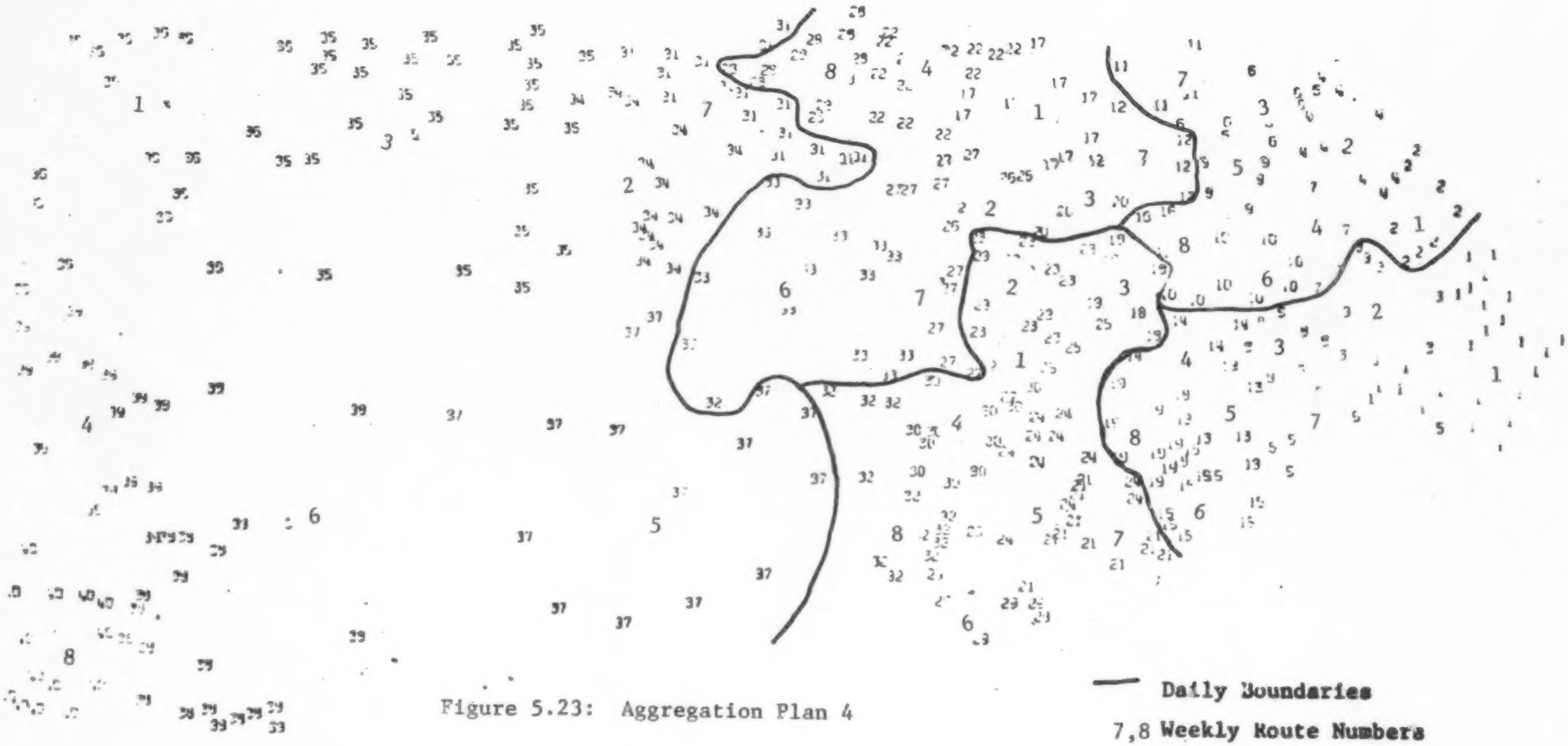

— Daily Boundaries
7,8 Weekly Route Numbers

Figure 5.23: Aggregation Plan 4

Aggregation 1 (refer to Figure 5.20)

Total Distance Cost = 1739.57
Continuous Routes = 11

Routes	Districts				
	Monday	Tuesday	Wednesday	Thursday	Friday
1	15	1	2	20	34
2	19	3	4	22	40
3	21	8	6	17	33
4	24	5	7	27	39
5	25	10	12	26	36
6	29	13	9	28	38
7	30	18	11	31	35
8	32	14	16	23	37

Aggregation 2 (refer to Figure 5.21)

Total Distance Cost = 1436.00
Continuous Routes = 14

Routes	Districts				
	Monday	Tuesday	Wednesday	Thursday	Friday
1	1	10	9	21	38
2	2	4	6	24	35
3	3	7	11	29	40
4	5	14	12	30	24
5	8	16	22	27	31
6	13	18	20	32	36
7	15	25	26	37	39
8	19	23	17	33	28

Table 5.2: Minimum Distance Aggregation Results

Aggregation 3 (refer to Fig. 5.22)

Total Distance Cost	1755.12
Continuous Routes	12

Routes	Districts				
	Monday	Tuesday	Wednesday	Thursday	Friday
1	13	7	9	20	33
2	15	1	12	27	40
3	19	3	6	28	35
4	21	2	11	22	36
5	24	5	10	25	38
6	29	8	16	26	34
7	30	3	17	31	39
8	32	14	18	23	37

Aggregation 4 (refer to Fig. 5.23)

Total Distance Cost	1684.01
Continuous Routes	14

Routes	Districts				
	Monday	Tuesday	Wednesday	Thursday	Friday
1	2	1	25	17	36
2	4	3	23	26	34
3	6	8	18	20	35
4	7	14	30	22	39
5	9	13	24	27	37
6	10	15	29	33	38
7	11	5	21	12	31
8	16	19	32	28	40

Table 5.2 (continued)

5.7 Districting the state-of-the-art

The state-of-the-art in solid waste districting is still fairly limited. Districting algorithms exist, but it is still not clear that they are usable for policy analysis or the actual detailed routing of the trucks. One of the major areas of weakness is the data: nobody has a really good idea of what will be generated in which area on what day. Beyond this problem (which will be discussed in detail in Chapter 7), the districting methods themselves do not do very good jobs in generating areas for collection. The results using street segments are encouraging, but there are still a large number of streets left in new odd nodes, where an intersection which could be divided into two routes without causing any extra travel time for either truck is instead split to cause extra travel for both. The effect of this problem will be covered in the following chapter. It is sufficient at this time to say that an "optimal" solid waste districting algorithm would attempt to equalize workloads without creating extra odd nodes in the community (by dividing boundary intersections 2-2 instead of 3-1, for example: see figure 5.24) and with reasonable compactness in the districts. At the other end of the scale, it would be desirable to have an even quicker method for districting as part of a simulation program for evaluating possible policy changes. The present method is not quick enough or inexpensive enough to be used in conjunction with such a simulation.

Still, the districting technique appears usable even in its present form. A community the size of Brookline could be districted in about a man-month, considering data preparation, actual district generation, revision, and preparation for routing. This is considerably less than other available methods would cost, although it might be possible to do even better manually in some cases.

One promising area for research is to use man-machine techniques such as have been developed by Krolak for truck routing (67). In such a system, an individual who knows the community uses computer aids for displaying and improving districting plans, and uses his own understanding of the area to do the actual evaluation of the plans as they are generated. This, though, requires explicit coding of the street network and is therefore probably infeasible for solid waste applications. There are other possible approaches: for example, an heuristic could be developed to trade-off workload equality and the generation of excess odd nodes to create districts explicitly useful for solid waste, and not also for political districting problems. The transportation problem based methods appear to be the most suitable, requiring only codes that are probably already available and giving satisfactory results fairly quickly.

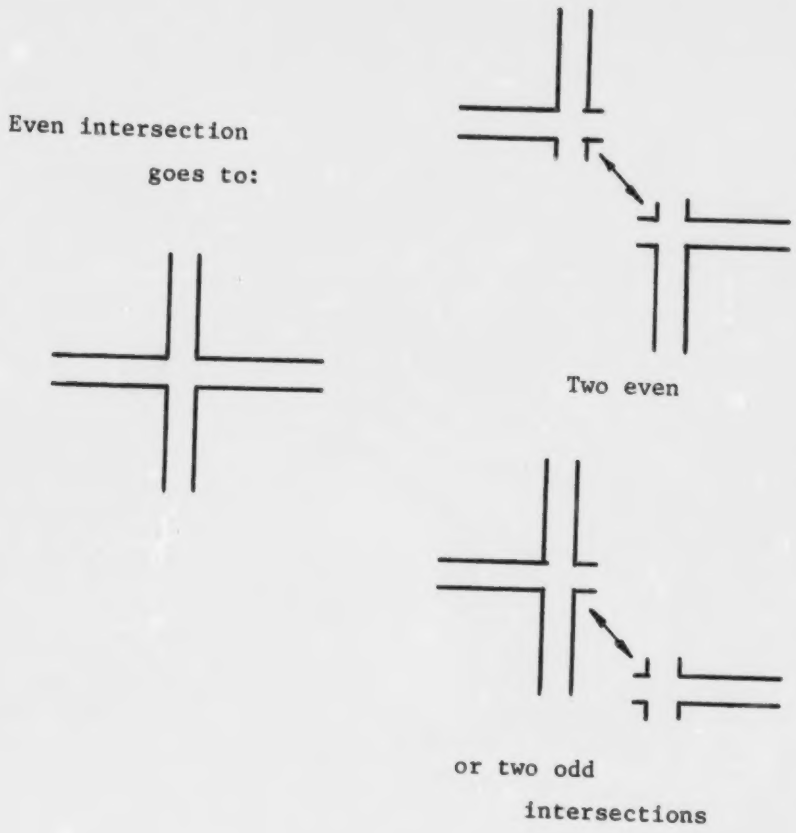

Even intersection
goes to:
Two even
or two odd
intersections

Figure 5.24: Sample Intersection Split

This is also an important direction for research. It seems at this time that districting techniques could be used for developing solid waste route plans, although more research would be desirable since the algorithms available are far from perfect.

ROUTING WITHIN DISTRICTS

The first stage of the chosen approach to the general routing problem was to decide which vehicles should cover what collection loads. The second stage defines actual routes for this coverage, which has been defined elsewhere as the microrouting problem (99). In some situations this "districting then routing" method fails. A clear example of this is the standard commercial collection problem of servicing a set of large containers widely dispersed through the community: routing for minimum travel time is important and district shape useless. Another example, satellite collection vehicles, fails under this approach because the detailed vehicle routes depend on the actual loads received; districts are defined as the total area for the mother truck and all satellites. This section develops a simple and flexible routing technique for use within predefined districts. Minimizing excess travel time unecessary milage will save on costs and vehicle wear. Fixed routes also give the system managers a better idea of how much the trucks have collected at each time during the day and show explicitly what work remains in the case of a breakdown. This would be of value in daily operations management, when combined with a good communications system (9).

6.1 Theoretical specification of the problem

Routing problems have been discussed in the operations research literature since the beginnings of the discipline: a classic is the Hitchcock transportation problem (40). There have been two basic types of routes discussed, depending on whether the service points are concentrated at the nodes of a network (e.g. Dumpster boxes) or on the arcs. For residential collection, arc collection seems more suitable: the truck travels each street in the community picking up whatever waste is there (at least in curbside collection). Figure 6.1 shows a simple network with arc and node demands placed on it. Node routing problems fall under the general class of travelling salesman problems in the literature, with extensions to multiple routes as the "truck dispatching problem" or the "N-salesman travelling sales man problem". Arc-routing problems are known as the "chinese postman problem" or the "M-postman chinese postman problem" for the multiple route case. Many optimal methods exist for solving the single-route problems of both types. These methods lead to tours which meet all demands while travelling the minimum amount. Heuristics, for which optimality cannot be proven, can solve the problems much faster than the strictly optimal methods. Extensions have also been made which attempt to consider the problems of mixed networks (with both two-way streets, instead of just a single type) and which make the problem more realistic in other ways. For example, the basic

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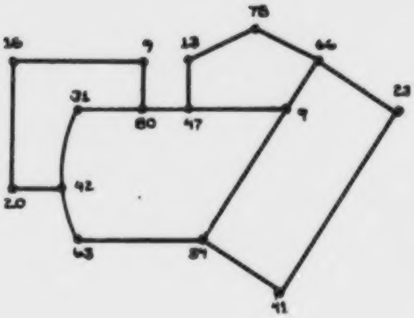
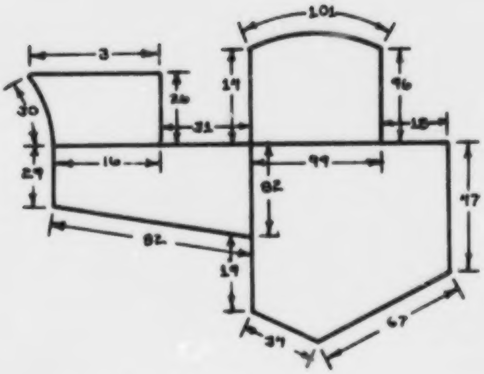

78
16
9
13
66
31
23
80
47
9
42
20
63
89
91

Node Demands


101
3
19
96
26
30
31
15
29
16
99
82
97
82
19
39
67

Arc Demands

Figure 6.1 :   Demand Characterizations

questions do not consider the difference between left and right turns, and often do not even look at the time lost from U-turns. Since optimality is usually only slightly better than the solutions given by the heuristics and since the problem statements are somewhat unrealistic at best, we have not attempted to develop optimal procedures for generating routes, but instead, looked for heuristics which will be about as good and much more useable.

Orloff (99,100) has combined the travelling salesman and chinese postman problems into one unified statement, the generalized routing problem. His work with school bussing suggests that loads could be looked at as a few people at fixed points (point demands) and also roads with a large number of stops (arc demands). He developed manual methods for quickly solving such problems which ressemble those described below for simple chinese postman problems. Unfortunately, he did not extend this to the multi-route case.

6.2 The Traveling Salesman Problem:

Routing for Dispersed Demands

There are two areas in solid waste collection where the problem of collecting from the nodes of a network is a good model of the collection process. In Brookline, for example, the project faced the problem of routing a truck called the "Alley Cat" which collects from areas where the larger packers cannot. These points are spread throughout the town with comparatively long travel distances between them. On a more universal level, consider the problem of routing a truck which collects from large containers, such as Dumpster boxes. This type of container is often used for apartment building or office waste in urban locations. The truck may be able to collect from five or ten such collection points before returning to the transfer station or disposal area. Other applications include routing for bulk collection of auto salvage. The objective is to minimize collection time while performing the necessary collections.

In solid waste work, one is almost exclusively concerned with the m-salesman travelling salesman problem, where cost considerations and problem size make the optimal algorithms generally unsuitable. Dantzig and Ramser (30) defined the problem and developed the first heuristic for it. Since then several superior algorithms have been developed.

In 1964, Clarke and Wright (28) developed an heuristic based on a fairly simple concept, and in many ways this has remained the state-of-the-art. They propose that the node furthest from the central depot (or incinerator) should be assigned first to the set of final routes: this eliminates the problem of having a group of unassigned nodes widely spread around the network. Any such nodes will be very close to the depot.

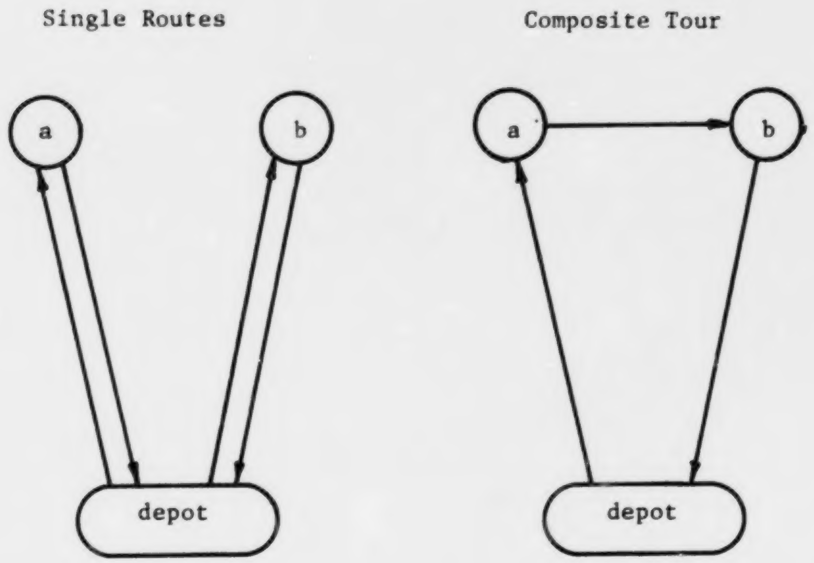
Implementation of this idea is also easy: choose an initial solution of servicing each demand on its own route. Then join these "routes", attempting to maximize the total time saved by combining them (see Figure 6.2). The heuristic does this by choosing the maximum savings at each stage without violating total route length and truck capacity constraints. While this procedure is myopic, it does follow the intuitive view of the problem described above since points far from the depot will be joined first. The results tend to be very close to optimality in most cases. Since the computer only sees the routes as points with time requirements and capacities, all stages are equivalent. A flow chart and and coding of the algorithms is given in Volume II. One advantage of the Clarke and Wright algorithm is its availability in commercial codes: IBM, for example, distributes a free version to computers using DOS, its Disk Operating System. The algorithm is also easy to program: the version used in this work was written, programmer, and debugged for under $30.

Recently, Beltrami and Bodin (15) have described a method for extending the Clarke and Wright algorithm to multiple pickups at network nodes. This facilitates accurate analysis of fixed container systems, where the number of weekly collections may vary depending on the establishment served (restaurants, for example, need much more frequent service than banks or apartments). While not directly applicable to residential waste collection, this approach could be of value in other solid waste applications.

One common procedure for solving the Truck Dispatching Problem is to solve the Travelling Salesman Problem for the whole system and then to break this optimal single tour into routes. The truck proceeds on its route until full, hauls away the load, and resumes the route. Although inefficient in terms of time and mileage, it enables the truck capacity to be used completely. It may be desirable to design long daily routes and then let the crews dump the truck whenever full for node collection operations. The individual node demands are highly variable: modelling them as deterministic to generate the shortest possible routes is probably unjustifiable.

Hausman and Gilmour (50) designed an exchange algorithm where customers are moved from one route to another to shorten the total time required. To get a computationally feasible method, they developed a regression estimate for route length depending on the variation in demand coordinates. This allowed them to quickly check the time savings for a route without computing shortest paths. This estimation procedure might be useful in developing lower bounds on the route lengths.

Krolak (75) developed "man-machine" methods for node-routing


Single Routes
Composite Tour
a
b
depot
a
b
depot

Savings: = ad + db - ab

Figure 6.2: Clarke and Wright Algorithm

problems. The concept is that a man can develop excellent multi-truck routes if computer aids are used for generating pictures of the routing plans and performing heuristics where desirable. The results using this techniques appear to be excellent; the major problem is cost. Still, timesharing terminals with large display screens now rent for under $100 per month, so that cost may be reasonable - especially in large private collection companies. It also appears that a similar "man-machine" approach would be suitable for districting, although the necessary development has not yet been done.

Recently, Lin and Kernighan (78) have published a description of an extremely efficient heuristic for large single route travelling salesman problems. The method uses exchange techniques, and is suitable for very large problems (over 100 demand nodes). However, it has not been extended to the multi-route case at this time.

Pierce (105)has solved certain Truck Dispatching Problems optimally using a branch-and-bound procedure. The method maintains a feasible solution, so that a good answer is available even if the program does not reach optimality. However, the storage and time requirements for large problems make it infeasible for application to solid waste problems.

Data accuracy is an important issue in node-routing problems. Distances and travel times must be found between the various demand nodes. It is reasonably easy (although time consuming) to construct a network of the streets which could be components of reasonable routes. Simple shortest path routines can then be used to find the meleage between the various nodes. However, travel time is the objective, not mileage, and travel speeds on different roads can vary a great deal. For waste collection, it is usually reasonable to assume the speeds to be deterministic, which reduces the size of the problem. Once this is done, the length of each network arc is made the time required to travel it, and the shortest path routine can be used to give the travel times between the demand nodes. Congestion is assumed to be exogenous to the solid waste system. It is only necessary to gather data on truck speeds on different types of streets and compare the derived travel times against real results.

In some situations it may be possible to use a model which does not require construction of a model street network. Instead, the coordinates of the demands are given and travel times found as a function of a simple distance metric. If necessary, barriers can be set up on areas where streets do not exist - for example rivers or golf courses - to make the times more accurate. This method loses somewhat in accuracy but is much simpler to implement. In many cases, though, the accuracy is not crucial. If the street network is sparse or made up of many winding roads, it should probably be coded. If not, a method based only on coordinates may be sufficient.

6.3 Routing the "Alley Cat": An Example of the Clarke and Wright Algorithm

In solid waste collection, routing to meet node demands is usually less important than to meet continuous demands. The node demands are a few fixed containers or special areas, and the arc demands the general residential collection. However, travel time is a more important factor when the demands are at separate nodes, so the possible gains from efficient routing are larger. In a deterministic system, total overall travel time should be minimized under constraints on truck capacity and route length. The amount of solid waste generated, though, is highly stochastic: generating the best three routes for the mean daily demand is useless if the last actually requires more than one load on a particular day, especially if the first two left some excess capacity.

The first stage in modelling the "Alley Cat" problem was to locate the demands in a network. Locations were provided by the Brookline DPW (see figure 6.3) and a street network built to include the demands and the most likely paths between them. These streets were assigned three speed classes to reflect size and congestion, and a shortest path routine was used to give the minimum expected travel times between the pairs of demands.

The Clarke and Wright (28) algorithm was then used to generate routes under a number of time and capacity constraints. The "Alley Cat" usually operates four days per week at three or four loads per day, so these routes were designed to require a maximum of 90, 120 or 150 minutes. The maximum capacity was measured in terms of people served and was varied from 400 to 480 per route. Link speeds and collection times were also tested at various values. Tables 6.1 and 6.2 show the results of two sets of sensitivity runs. Table 6.1 shows variation in the basic speed and travel time parameters, and especially the effect of this variation on the number of routes. In the runs of Table 6.2, these parameters are kept constant and the constraints relaxed, showing that the shortest routes occur as expected in the least constrained cases. Figures 6.4-6.7 show an example set of routes.

One way to increase the flexibility of the system is to design nearly optimal daily routes and allow the truck to go to the incinerator whenever full. This eliminates the problems caused by variations in the amount of waste generated, at the cost of a slight amount of extra time. Table 6.3 shows a set of runs of this type using the same speed and collection time parameters as Table 6.2. The "computed" times assume that the truck only returns to the incinerator at the end of the day. These are adjusted to include two trips to and from the incinerator each day in the "expected" times. Figures 6.8 and 6.9 show the routes generated in the last of these runs. As can be seen from the table, the cost in time of using daily routes is small, since

Run Number	Time Constraint (min.)	Capacity Constraint (people)	Col. I (min/capita)	Speed (mph)			Dominant Constraint	Number of Routes	Capacity Used		Time Taken	
				Class 1	Class 2	Class 3			Maximum	Median	Maximum /	Median
1	120	400	.15	10	15	20	Capacity	15	398	386	116.3	89
2	120	400	.15	8.3	12.5	16.7	Capacity	16	400	370	116.2	89
3	120	400	.15	7.1	10.7	14.3	Both	16	400	380	117.3	98
4	120	400	.20	10	15	20	Both	16	400	382	117.9	104
5	120	400	.20	8.3	12.5	16.7	Both	16	400	355	119.1	109
6	120	400	.20	7.1	10.7	14.3	Both	17	400	355	120.0	112
7	120	400	.25	10	15	20	Time	17	388	339	118.5	112
8	120	400	.25	8.3	12.5	16.7	Time	18	383	324	120.0	112
9	120	400	.25	7.1	10.7	14.3	Time	19	346	308	118.8	116
10	150	450	.15	10	15	20	Capacity	13	450	446	120	102
11	150	450	.15	8.3	12.5	16.7	Capacity	13	450	428	130	106
12	150	450	.15	7.1	10.7	14.3	Capacity	14	450	423	132	110
13	150	450	.20	10	15	20	Capacity	14	449	432	133	110
14	150	450	.20	8.3	12.5	16.7	Both	14	446	432	140	119
15	150	450	.20	7.1	10.7	14.3	Time	14	450	432	148	124
16	150	450	.25	10	15	20	Time	14	449	428	149.8	131
17	150	450	.25	8.3	12.5	16.7	Time	14	449	427	148	136
18	150	450	.25	7.1	10.7	14.3	Time	14	441	402	148	140.8

Table 6.1 Alley Cat Runs - Sensitivities (April 1972)

Speeds = 8,12,16 mph   Collection Time = .125 min/person

Run	Time Constr.	Capacity Constr.	Number of Routes	Total Time	Total Travel Time	% Travel
1	90	420	17	1354	564	41.6
2	120	420	15	1291	501	38.8
3	150	420	14	1258	467	37.2
4	90	450	16	1323	534	40.3
5	120	450	13	1255	465	37.0
6	150	450	13	1248	457	36.6
7	90	480	16	1318	528	40.1
8	120	480	13	1240	450	36.3
9	150	480	13	1220	429	35.2

Table 6.2 Alley Cat Sensitivity Runs

Run	Time Constr.	Capacity Constraint	Number of Routes	Total Time Computed	Total Time Expected
12	360	1300	5	1006	1249
15	360	1350	5	991	1243
18	360	1400	4	982	1233

Run	Travel Time		Expected % Travel
	Computed	Expected	
12	216	459	36.7
15	200	452	36.4
18	191	443	35.9

Table 6.3 Alley Cat Daily Route Runs

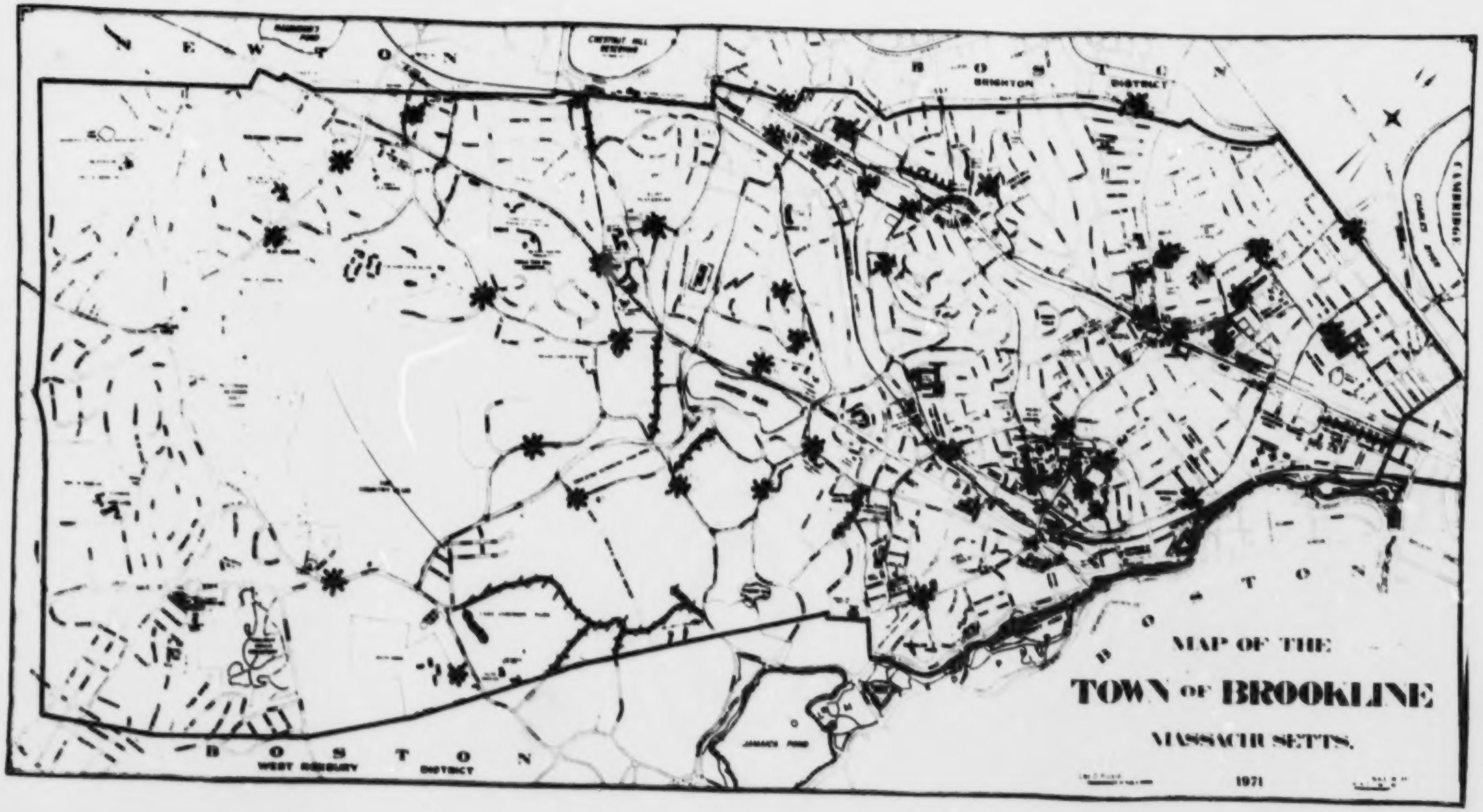
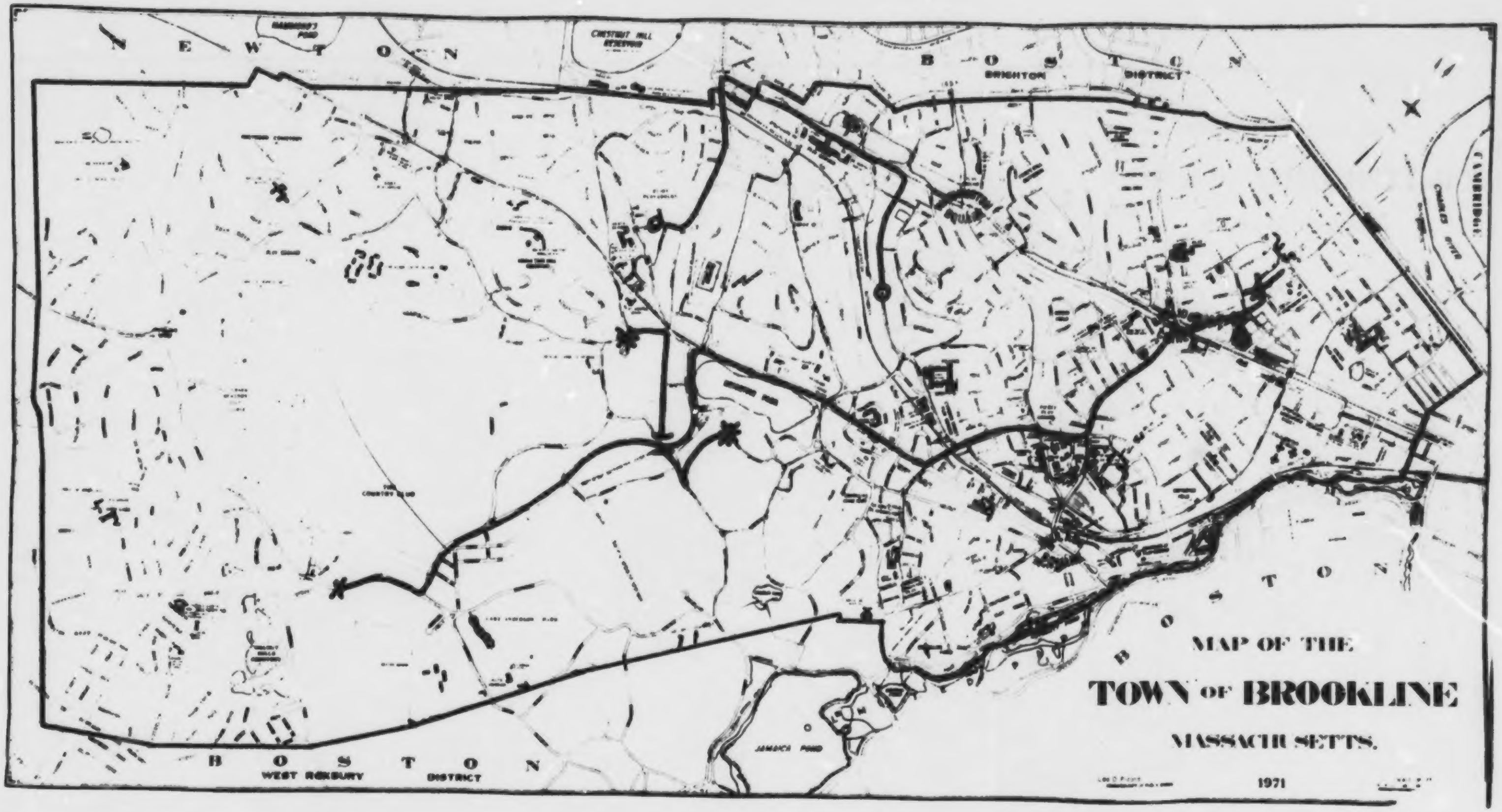

N E W T O N
CHESTNUT HILL RESERVOIR
B O S T O N
BRIGHTON DISTRICT
CAMBRIDGE
CHARLES RIVER
B O S T O N
MAP OF THE
TOWN OF BROOKLINE
MASSACHUSETTS.
1971
JAMAICA POND
B O S T O N
WEST ROXBURY DISTRICT

Figure 6.3: Alley Cat Demand Nodes



N E W T O N
HAMMOND'S POND
CHESTNUT HILL RESERVOIR
B O S T O N
BRIGHTON DISTRICT
CAMBRIDGE
CHARLES RIVER
THE COUNTRY CLUB
JAMAICA POND
B O S T O N
MAP OF THE
TOWN OF BROOKLINE
MASSACHUSETTS.
1971
B O S T O N
WEST ROXBURY DISTRICT

Figure 6.4 Alley Cat Single Load Routes (1-3)

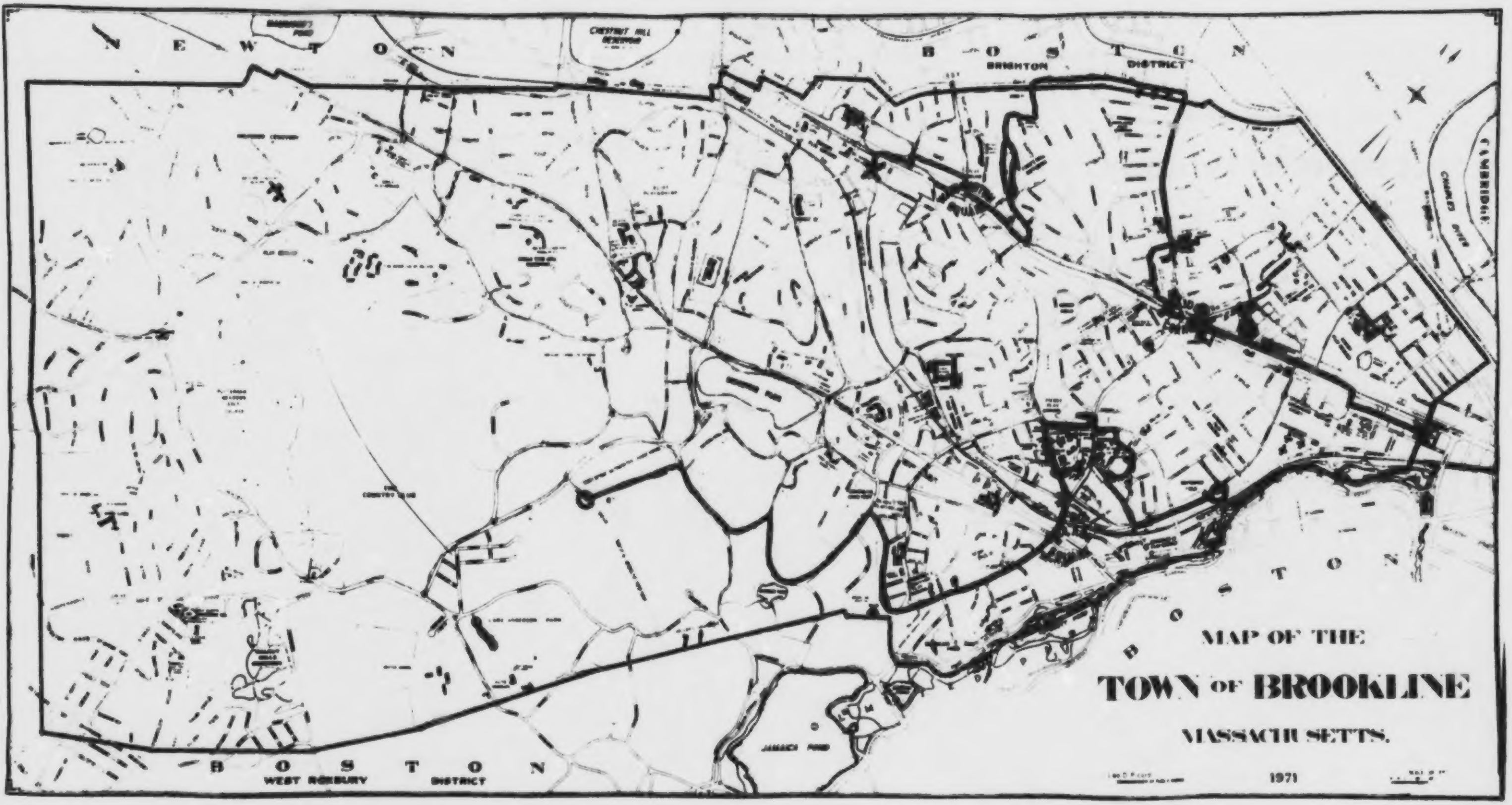

NEWTON
CHESTNUT HILL RESERVOIR
BOSTON
BRIGHTON DISTRICT
CAMBRIDGE
CHARLES RIVER
BOSTON
MAP OF THE
TOWN OF BROOKLINE
MASSACHUSETTS.
1971
JAMAICA POND
BOSTON
WEST ROXBURY DISTRICT

Figure 6.5: Alley Cat Single Load Routes (4-6)

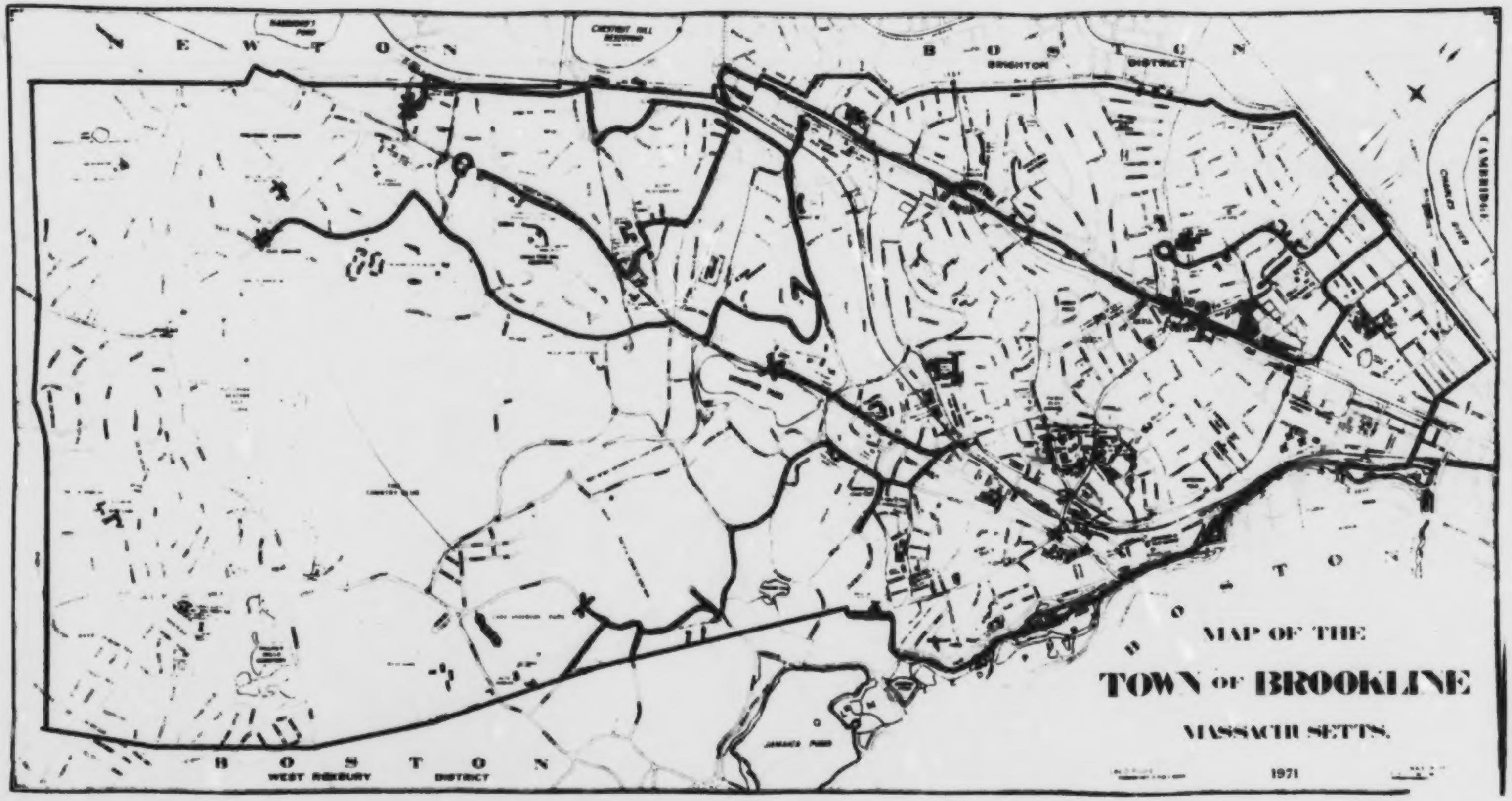

N E W T O N
HAMMOND'S POND
CHESTNUT HILL RESERVOIR
B O S T O N
BRIGHTON DISTRICT
CAMBRIDGE
CHARLES RIVER
B O S T O N
MAP OF THE
TOWN OF BROOKLINE
MASSACHUSETTS.
1971
JAMAICA POND
B O S T O N
WEST ROXBURY DISTRICT

Figure 6.6: Alley Cat Single Load Routes (7-9)

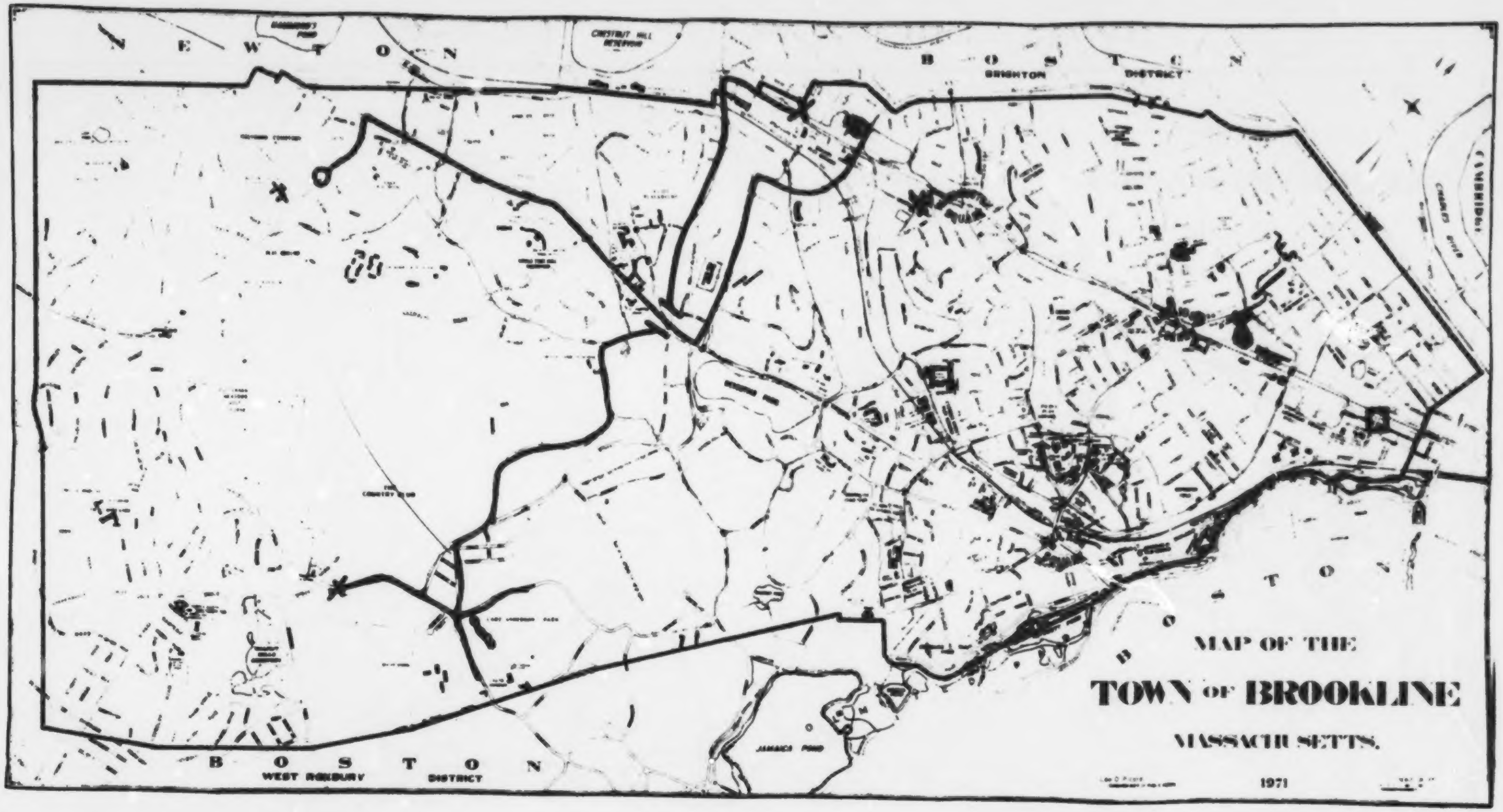

NEWTON
BOSTON
BRIGHTON DISTRICT
CAMBRIDGE
CHARLES RIVER
CHESTNUT HILL RESERVOIR
BOSTON
WEST ROXBURY DISTRICT
JAMAICA POND
BOSTON
MAP OF THE
TOWN OF BROOKLINE
MASSACHUSETTS.
1971

Figure 6.7: Alley Cat Single Load Routes (10-13)

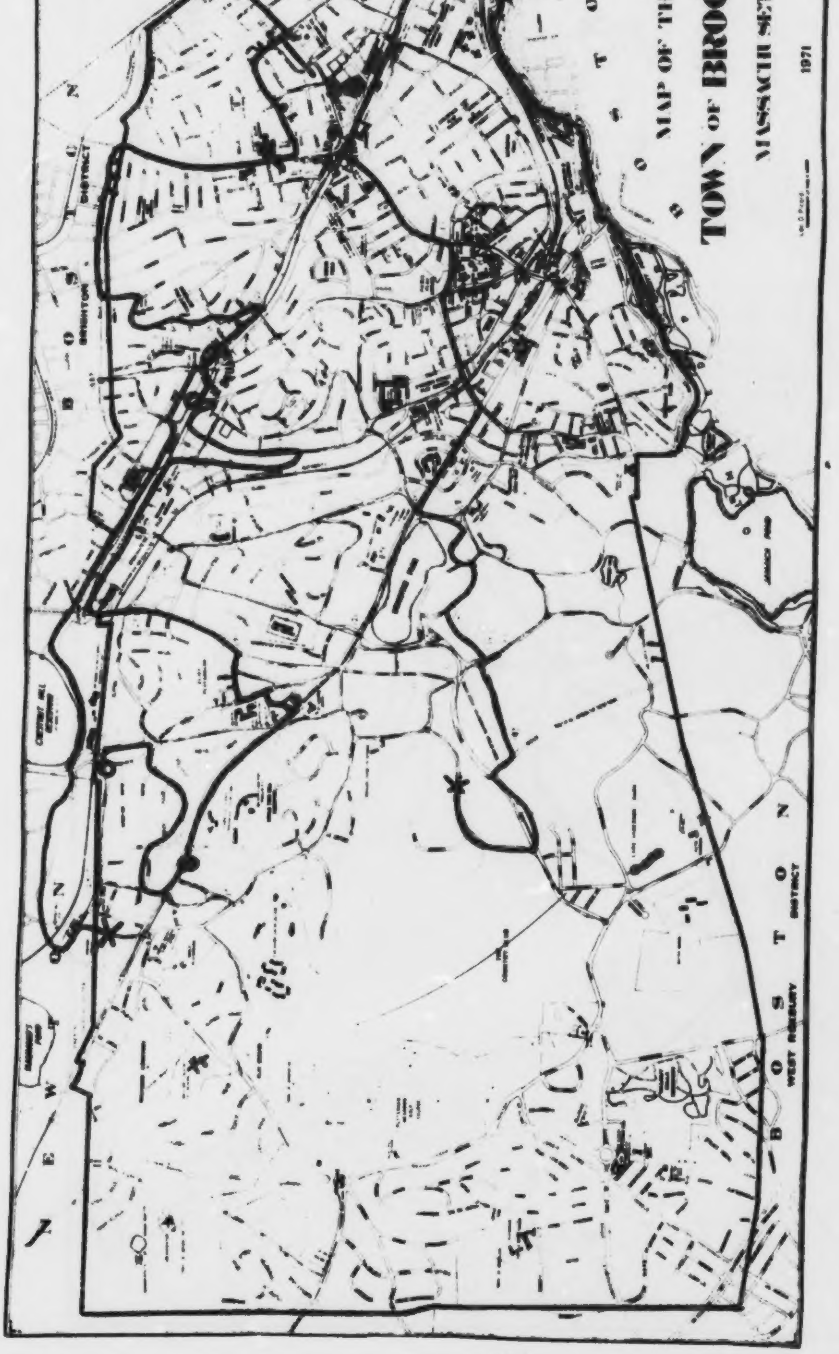

MAP OF THE
TOWN OF BROOKLINE
MASSACHUSETTS.
1971
CAMBRIDGE
CHARLES RIVER
BOSTON
BRIGHTON DISTRICT
NEWTON
WEST ROXBURY DISTRICT

Figure 6.8: Alley Cat Daily Routes (1-2)

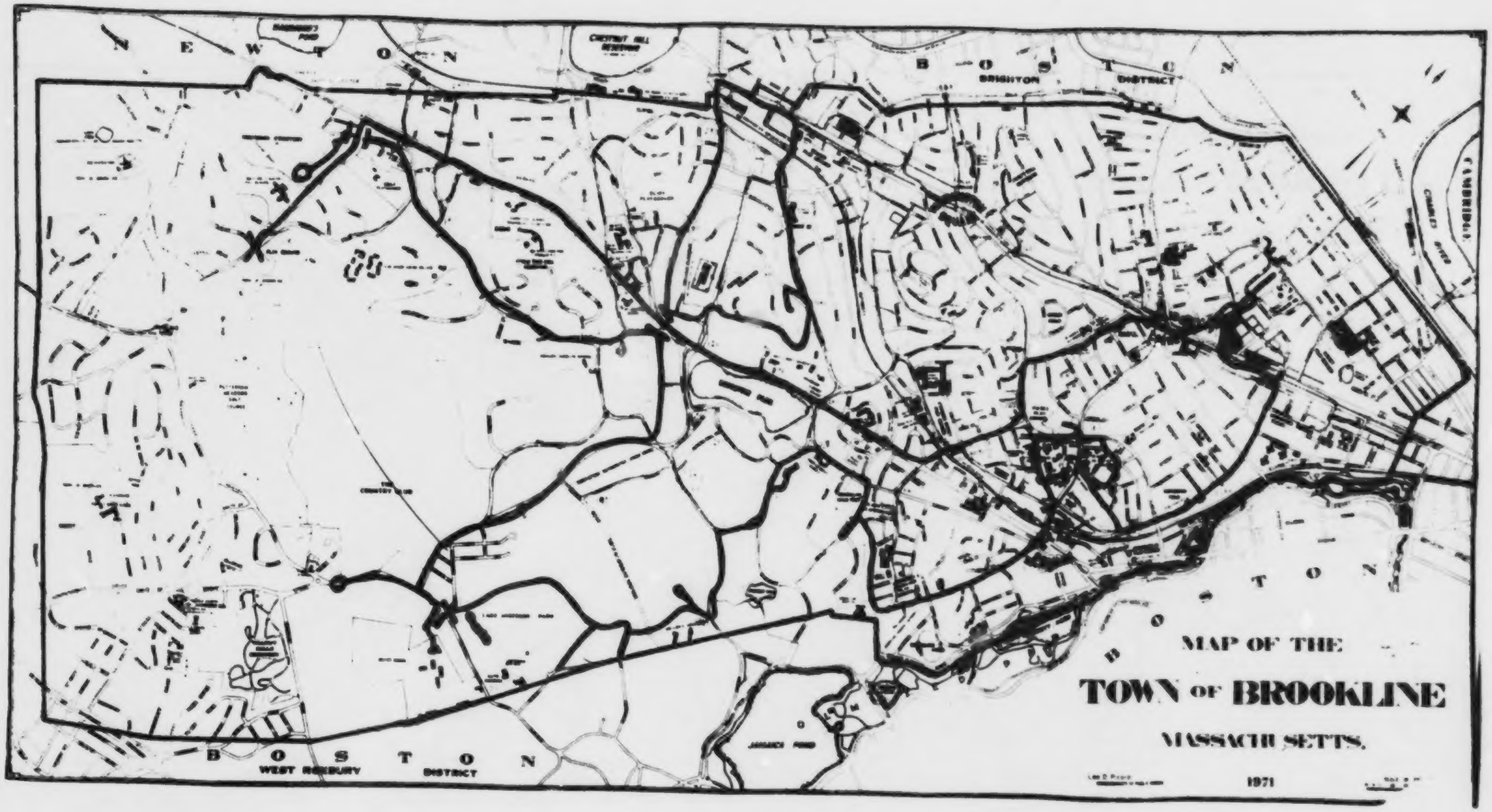

N E W T O N
CHESTNUT HILL RESERVOIR
B O S T O N
BRIGHTON DISTRICT
CAMBRIDGE
CHARLES RIVER
B O S T O N
MAP OF THE
TOWN OF BROOKLINE
MASSACHUSETTS.
1971
JAMAICA POND
B O S T O N
WEST ROXBURY DISTRICT

Figure 6.9: Alley Cat Daily Routes (3-4)

the inefficiency of the extra trips to the incinerator is balanced by the increased efficiency in routing the trucks to the demands. This daily route method is probably to be preferred in most cases, because available truck capacity is used much more fully.

6.4 Routing for Residential Collection: Arc Demands and the Chinese Postman

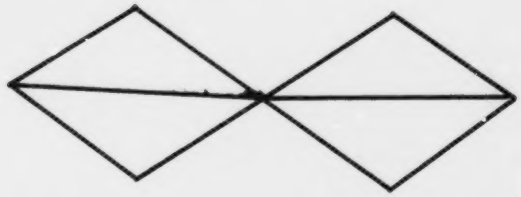
The Chinese Postman problem deals with covering all the arcs in the network while travelling the minimum total distance (or time, if the arc costs are the number of minutes required to travel them). Euler first formulated a version of this problem in 1736, in the famous problem of the seven bridges of Konigsberg, and discovered some of the basic properties of solutions. Mei-Ko reformulated it more recently, and generalized the ideas to consider not only which networks could be completely covered without retracing any arc, but also how to minimize the total retracing. Since his work discussed routes for postmen, and was published in the Chinese journal of mathematics, the name Chinese Postman problem was coined.

In actual solid waste problems, there are likely to be some streets which need not be traced -- either because they are collected by some other means (such as a special commercial collection truck) or because no one lives there, so no waste is generated for collection. This requires some generalization of the problem but little new insight is necessary.

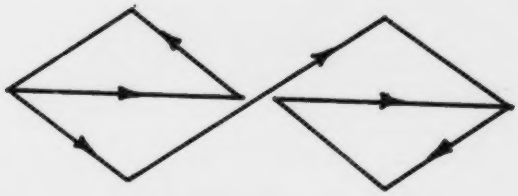
In the solid waste problem the network of interest is the streets of area covered in the collection district. The assumption of the problem is that collection has to be done on each street segment and that the collection demands are distributed along the street segments. This is a reasonable model most of the time, although pathological cases where it fails can easily be generated.

The key concept in this type of routing is the idea of the "odd node" - an intersection with an odd number of arcs incident upon it. Odd nodes cause the truck to repeat a street segment. Consider, for example, a "Y" shaped intersection, that is, an odd node with three incident arcs. The first time the truck passes through this intersection it collects from two of the arcs. On the second pass, it collects from the third, reaches the center of the "Y" and must travel down one of the three arcs a second time. The same is true of intersections with five, seven, or any other odd number of branches. Dead ends are the trivial case of one-branch node.

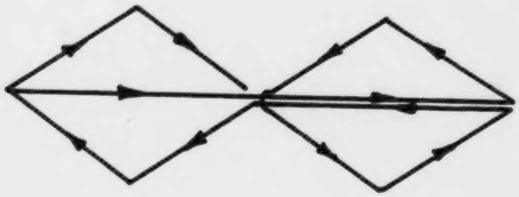
The simplest algorithm for solving this problem, proposed by Bodner, Cassell, and Andros (17,139) uses a random walk procedure. A route, started at some point in the network, proceeds down uncollected streets, randomly choosing between open streets when it reaches



Simple Street Network

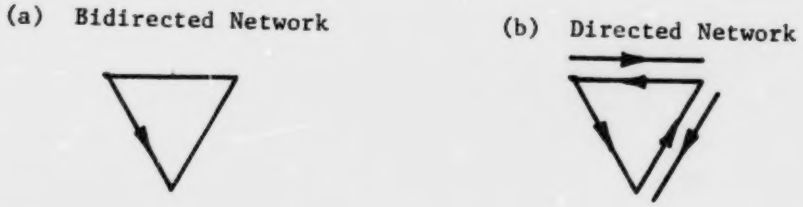


Euler Tour



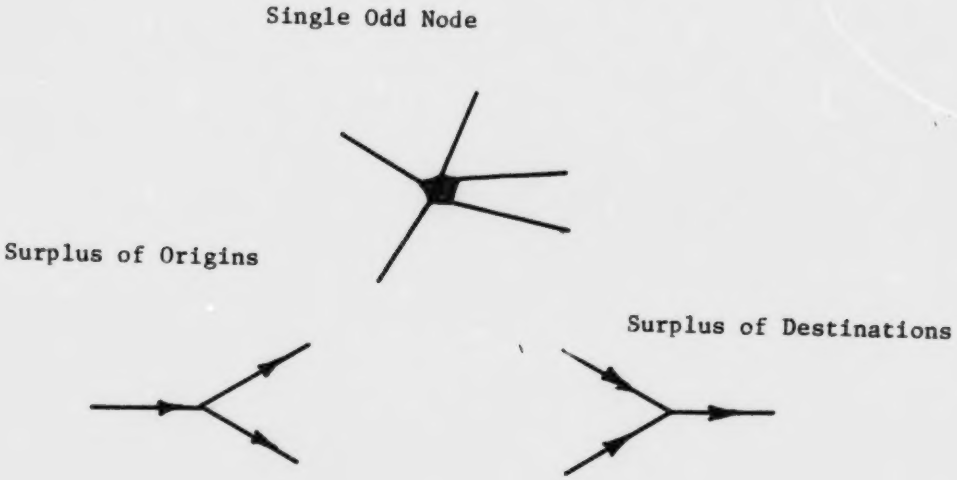
Random Walk

Figure 6.10: Tour Characterizations


(a) Bidirected Network

(b) Directed Network

Figure 6.11 : Network Directedness


Single Odd Node

Surplus of Origins

Surplus of Destinations

Figure 6.12: Graphic Definitions

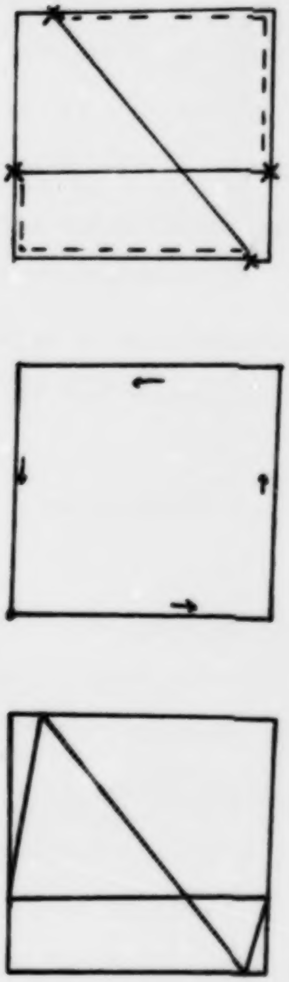
blocks give right turns, which are better than counter-clockwise loops with left turns. The example they show for single-side collection combines tours with the node-pairings developed using a method similar to Liebling's to give nearly optimal routes. Their work could also be used in Euler tour design after use of an algorithm such as Stricker's (as described below). It is interesting to note that some simple manual methods for solving the Hitchcock problem do exist. Lofy, for example describes one in his work (80).

Stricker (85, 125) faced a more difficult for solid waste collection problem. Most agencies collect from both sides of small streets at one time, so the arc can be travelled in either direction. This leads to the "matching problem", which has only recently been solved for large problems. No a priori way exists to determine whether a node should be an origin or a destination. Several algorithms for the matching problem have been suggested, such as those by Murty (97), Glover (45), Edmonds (34), and Edmonds and Johnson (35). All can solve small problems such as single waste collection districts, but they would be expensive and would have difficulty solving networks with both one-way and undirected streets.

The most efficient of these methods is the "Blosson Algorithm" described in Edmonds and Johnson. A computerized code for this algorithm will soon be available, and should be investigated if facilities for using it are also available. The major costs in routing analysis, though, are not in using the algorithm but in coding the network for input and computing shortest paths between each possible pair of odd nodes. An efficient manual method would be much more satisfactory.

To provide such an alternative, Stricker suggested that small problems such as solid waste routes for individual collection trucks could best be done visually using a map and several heuristic rules, which would be optimal if exhaustive searching was performed.

To understand the method, it is important to see the concept of a negative cycle. Consider any loop in the network, starting and ending at the same point. Now assume that some part of this loop is on the list of arcs to be travelled twice. If this part includes more than half of the loop then total distance can be reduced by including instead the other part of the loop to be travelled twice. For a trivial example, consider two arcs in a "D" shape. If the curved portion is covered twice, distance could be saved by using the straight portion instead, without changing anything else. This is the key to the algorithm, and a loop like this where more than half the length is travelled twice is a negative cycle. Figure 6.13 shows a slightly more



Simple Street Network

(x = odd nodes, dotted lines show the initial pairing)

Negative Cycle

Final Network

(new arcs show streets which must be covered twice on the route)

Figure 6.13: Stricker Routing Example

complex example and a verbal description of the algorithm is given below:

1. Identify and mark the odd nodes for easy bookkeeping
2. Choose a set of feasible pairings.
3. Inspect these pairings looking for negative cycles.
4. If a negative cycle is found, for example on loop ABCDA (whereAB and CD are paired) reverse the pairing to instead pair BC and DA. Go back to 3 and continue the inspection for negative cycles.
5. Distance is minimized when no more negative cycles can be found. Use the added arcs to form an augmented even network, and generate Euler tours on this network to meet secondary objectives.

Stricker also gives suggestions for using this method as a basis for solving the similar m-Postman Chinese Postman Problem, which assumes that m trucks collect from the network. This more complex problem implicitly establishes the districts: the plan could put all N-S streets on one route and all E-W on another). To simplify management, most collection systems, do not allow this. With fixed districts Stricker's suggestions facilitate the design the exact boundaries between two truck routes in a rational manner. A set of compact and equitable districts can fairly easily be turned into nearly optimal detailed truck routes.

The method utilizes the insight of the route designer as much as possible: factors beyond the ability of the totally computerized versions may be taken into account. For example, routing for one-way streets can be done by drawing the Euler tour to do them first, and then filling in the remainder. Busy streets which require collection on only one side at a time are routed as if they were two one-way streets. Segments which do not require collection are ignored in identifying odd nodes and drawing the Euler tour, but are allowed in the matching process: they are, therefore, only traveled when they save time. Fast streets can easily be given precedence over slow or congested ones when identifying the negative cycles. Many of these factors are beyond the capability of the available computer routines. All, though, are simple variations on an uncomplicated technique. It might be possible for the routes to be designed by the drivers, who have the most insight into the system and gain most from improved routes. The gains will be small - probably about ten percent on mileage, perhaps as much as five percent of the total time: still thirty minutes per truck each day may represents substantial annual savings if the uses for the time can be found. Future research should investigate the expected gain of route improvement.

6.5 Routing Trucks in the Districts: Examples of the Strike Method

Given a good district, route generation follows easily. The procedure is:

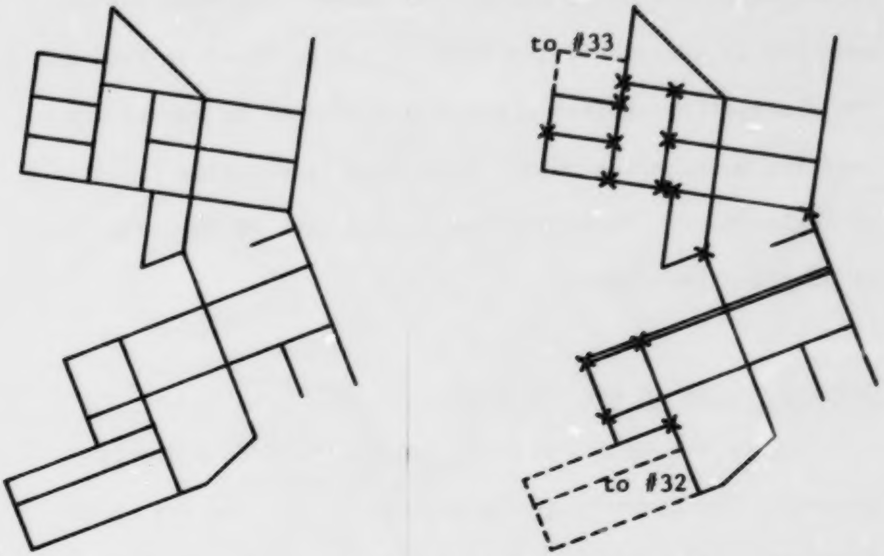
- finalize the route boundary
- pair odd nodes optimally
- generate Euler tours

The street network of one district generated is shown in Figure 6.14a. A Simple ad hoc modifications eliminate several odd nodes. (Figure 6.14b). The remaining odd nodes are then marked and initially paired (Figure 6.14c), with this pairing revised to the optimal (Figure 6.14d). Optimality cannot be proven in this case, but careful although not exhaustive search finds no negative cycles thereby suggesting that optimality has been reached. Three Euler tours are generated (6.14e) attempting to minimize the number of U-turns. The best of these, the last, should probably be the truck route -- although there may be one-way streets in the region which would make this route unfeasible. Note that both sides of one street must be collected separately, and are in this route. Similar routes were designed for three other districts from figures 5.7 and 5.8, and are shown in Figure 6.15.

Since areas must be transfered from one district to another so that streets are not collected twice, block face data is used implicitly. One alternative is to design the Euler tours to allow these boundaries to be collected by both trucks near the end of the day. Whichever finished earliest would then collect the boundary. This, though, does not seem very satisfactory. The time requirements in this stage of the analysis probably make the design of multiple sets of routes for one area infeasible. Given accurate data, the system in this form is probably as accurate and less expensive than manual routing, but not as quick or flexible as desired.

The routing process itself can be done very quickly and easily, given the correct boundaries. Ten minutes per route would be a reasonable time requirement so a full plan for a 40 route system could be generated in a man-day, or an hour for each driver. Copies of the maps or lists of the streets traveled would be the output. Since the districts are mostly small, it usually will not matter where the truck gets filled: the difference in travel times to the incinerator between points on the route will be insignificant. For a few districts, though, it might be desirable to build the Euler tour so that its midpoint is as near the disposal point as possible.

In fact, the large number of possible Euler tours makes it possible to consider many secondary objectives of this type. Obvious ones

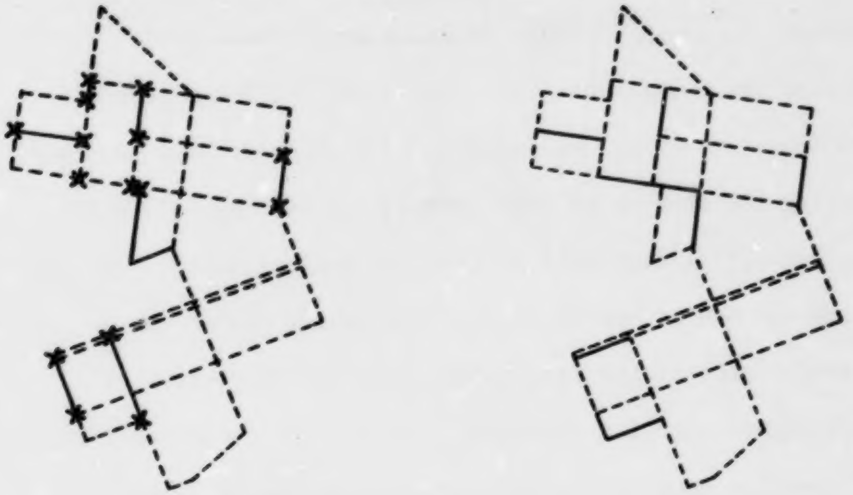


(a) Original Street Network

(b) Revised Street Network
(x = odd node)

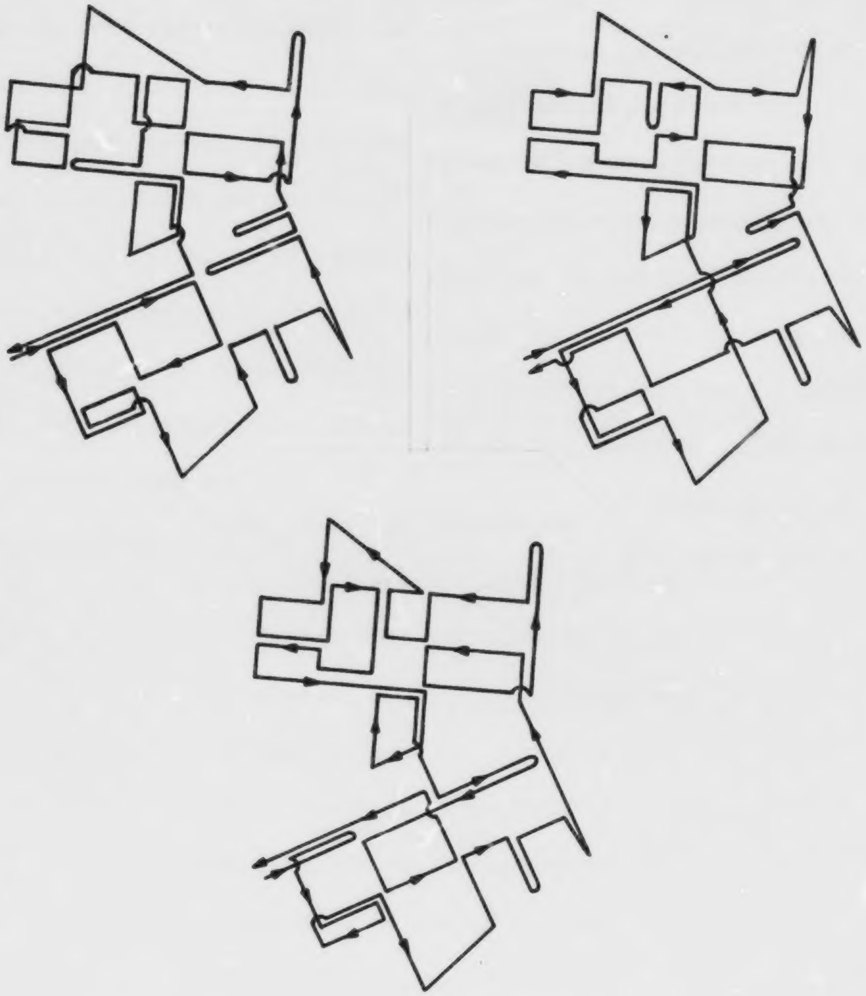
(c) Initial Pairing of odd nodes

(d) Final Pairing



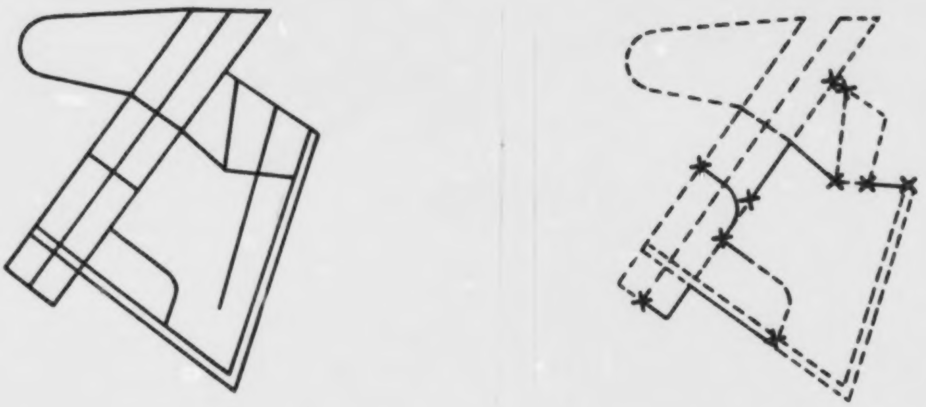
(Solid Lines are street segments to be covered twice)

Figure 6.14: Another Stricker Example



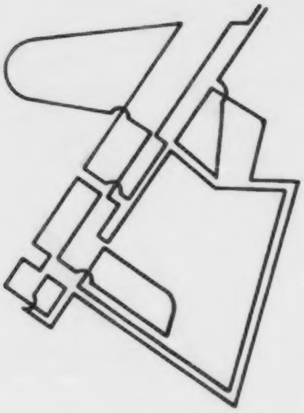
(e) Three possible Euler tours.

Figure 6.14 (continued): Stricker Example



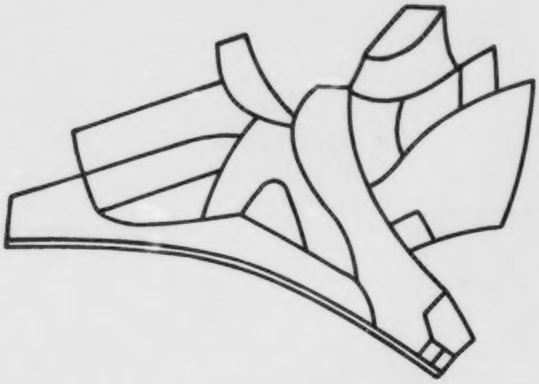
Assigned Blocks

Paired Odd Nodes

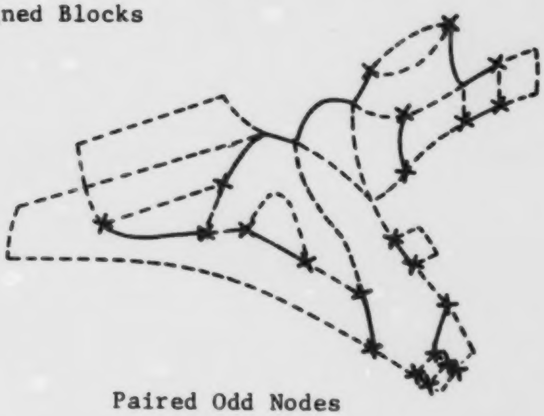


Euler Tour

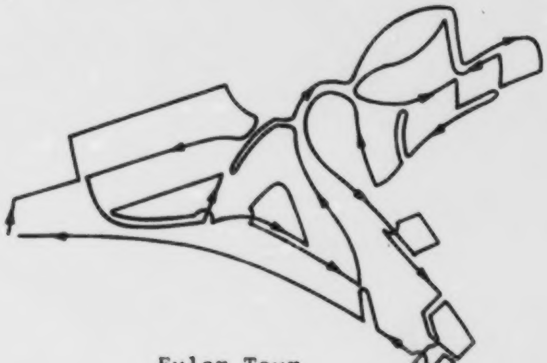
Figure 6.15: Brookline Routing (District 4).



Assigned Blocks

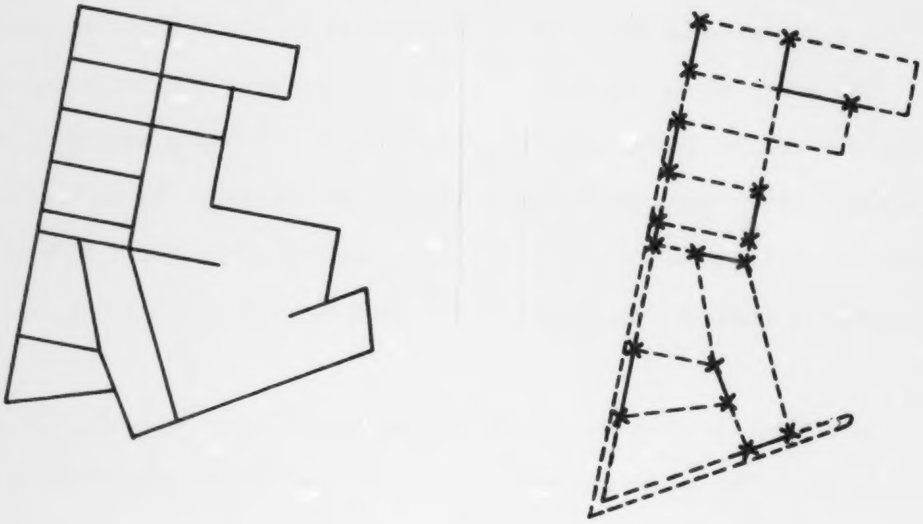


Paired Odd Nodes



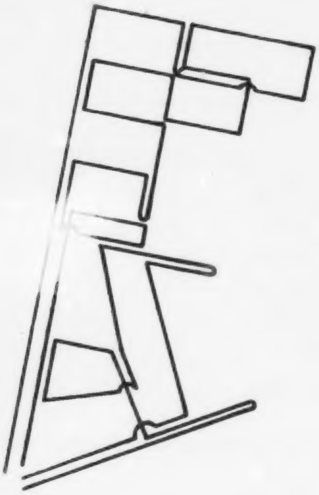
Euler Tour

Figure 6.15 (continued): Brookline Routing (District 7).



Assigned Blocks

Paired Odd Nodes



Euler Tour

Figure 6.15 (continued): Brookline Routing (District 33) include minimizing U-turns and traveling one-way streets in the right direction. Shuster and Schur's suggestions on clockwise loops are clearly valuable (141). Topography, though, is also important: some steep streets may effectively be one-way. Timing of collections can be attempted, so that the mayor has his waste collected at the best time for him, for example. Areas serviced last may be near the beginning of the routes for the following day, if desired. If these secondary objectives are stated, they can be used in the routing. In most cases, the large number of possible Euler tours allow such secondary objective to be satisfied. A totally computerized routing system would not allow this flexibility.

At present, the routing algorithm seems to be both adaptable and easy to use. While the interface with the districting routing still requires some development, the routes produced seem to be able to satisfy all the stated goals for solid waste collection routes. They are fair and efficient, and can be produced and revised at fairly low cost. The limitations are only in the time required and in the need for accurate disaggregated data on the collection time requirements, whether found from direct measurements or by analysis of population and housing information.

6.6 Future Improvements in Routing Techniques

The development of better methods for arc routing is an interesting problem, but one in which there is likely to be little further gain. The detailed microrouting of vehicles reflects complex interactions of many factors, even when the districts are fixed and the streets to be covered are known completely. Methods like Stricker's minimize the mileage travelled, except in some specific special cases where pathological configurations of one-way street exist. Generation of clockwise tours and consideration of one-side and both-side collection should also be possible. Extensions to cases with both node and arc routes seem possible, using results such as Orloff's (99). Further research should look explicitly at the tradeoffs involved between such things as extra mileage, left turns, or travel through busy intersections. It would also be desirable to design the routes so that hauls occurred as much as possible from points close to the disposal site, to collect at approximately the same time each week from each house. and to define and meet other similar goals. The use of microrouting techniques in practice will make it possible to at least formulate these special (and route dependent) goals, so that methods can be developed to explicitly consider them.

The algorithms discussed are not fool proof. They require some understanding of the goals of the system, and significant knowledge about its special features. It seems desirable to use them internally in the collection system. One possibility is to train the actual drivers to design the routes, dependent on their experience and their desires to finish work as quickly as possible. One expects this to work much better in an incentive system, than in one operating under a total hours method. The manual techniques are simple enough for clerks in the system to design routes, so that is another alternative. In any case, the microrouting should be done by the people actually concerned, instead of outside consultants with no applicable experience except in the techniques.

The interface between the microrouting and the district design is an interesting one. While our discussion has centered around the questions of data and the compatibility between census block statistics and segment-oriented routes, there are some significant implications for districting in the routing process. Consider a simple 4-street intersection. That has an even node, but if it is at the boundary between two routes it may be divided into either two even nodes (2 and 2) or two odd nodes (1 and 3). (see figure 6.16). A districting procedure which attempted to design boundaries without increasing the number of odd nodes would be ideal for the collection problem.

The question of the best combination of node routing and arc routing for a particular system is unanswered. The question is how much effort should be spent in local street collection, and how much should be allocated to collecting from large loads at fixed points. A generalization of this issue looks at how the system should attempt to divide the loads between fixed containers and simple collection, either from curbside or back-of-house. This issue cannot really be investigated until a better understanding of the issue involved in the two basic types of collection is achieved. The microrouting problem has not been solved "optimally" at this time, but the techniques so far developed should enable a system operator to generate a very good set of routes given the districts to be collected by each vehicle on each day. Costs will be low, and results excellent.

CENSUS DATA BASED ECONOMETRIC MODELS
FOR PREDICTION OF WASTE GENERATION AND COLLECTION TIMES

Earlier chapters have described the development of districting and routing algorithms. All of the districting plans require some measure of the anticipated waste, and these estimates must be on a sufficiently disaggregate level to enable partitioning of the area under consideration. One alternative is to simply measure the volume of waste on several occasions and use this data to predict solid waste quantities. Even this expensive exhaustive approach leaves open issues such as when should measurements be taken, how can we be sure the samples are representative, and what causal factors lead us to anticipate variation. This chapter deals with these several issues in proposing a census data based econometric model for prediction.

7.1 Data Requirements and Sources

The first issue that must be defined is the scope of the system under consideration. Exactly who is serviced by the municipal collection services? This chapter's primary focus is on systems serving residences: extension to include commercial or industrial collection will be introduced. Further, many of the models to be developed assume certain system characteristics, for example, curbside pickup, separate dumpster collection, and so forth. These particular assumptions and possible extensions will made explicit.

Input to the districting algorithms consists of some "population" measure; in the case of interest this measure can either be estimated waste quantity or anticipated workload. Workload (in time required for collection) cannot be predicted directly from census type indicators. Instead one expects the work to depend upon the amount of waste, number of parcels, truck travel time between pickup points, travel time to the point of collection (i.e. curbside, backyard), factors such as density of waste, size of items, fatigue, and finally haul time to disposal point. Therefore, this chapter first develops models to predict waste output, and then models to predict collection time. Comparison of districting plans based on the two approaches will be made in chapter 8.

An alternative for either result, is direct measurement of the outputs. Even for a single comprehensive measurement, the costs are significant and the accuracy suspect. Further, a single survey might lead to spurious results; it does little to enhance one's

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understanding of the spatial and temporal variability of waste production. Most existing data is on a highly aggregate level (i.e. waste per town by months). In requests to over 30 agencies, none were able to supply data on a sufficiently disaggregate level for districting purposes, unless, that is, one could establish homogeneity across districts. In such a case total daily route loads become useful.

The models developed herein are based on pre-existing and universally available data rather than on any sparsely available public works or similar data. The "third count" census data (broken down to a block level) is the most widespread resource of this type: included is information on population and housing Other census data at the block group or enumeration district level may be useful. To supplement this data, one might investigate zoning information, police census, tax assessments, and whatever auxiliary data that can be accessed. Census data is only available at ten year intervals (plus lags for processing) -- a town intent upon an efficiently running collection system might consider periodic updates and revisions of the census data to insure a more accurate effort. If business, commercial, or industrial sources are to be included in regular collection, these may be dealt with individually if the numbers are sufficiently small; otherwise, sources such as the census of business, local liscencing bureaus, or tax and zoning statistics might be consulted in developing predictive models. DeGeare and Ongarth have shown that commercial waste generation is correlated with the number of employees, business hours, and the character of the business. Finally, when developing the time based workload models, geographical information such as road milages and block areas (as measured from maps or available from town engineers) are necessary.

7.2 Choosing One Level of Operations

To complement the input requirements described above, certain decisions must be made prior to the actual modelling. Specifically, the operating policies for the system must be defined along with their implications upon choosing a design level. Two important causes of inaccuracy can be cited. First, waste generation and collection time vary randomly due to short range effects of weather, proximity to holidays, moves from a neighborhood, and so forth. Second, there are major seasonal trends plus long range variations in waste production accounted for by increasing population, new developments, changing consumption patterns, and similar phenomena.

Consider the annual variation. The total waste may vary from less than 50% to over 150% of the base load. One sees this in

Figure 7.1 depicting work by Kennedy (65). This variation may be caused by a variety of factors including seasonally varying consumption and eating habits, lawn or yard waste, and population changes (for example, a resort community). One example the project looked at was an 18 year history, by months, of the waste produced in Ocean Grove, New Jersey. Fourier analysis showed significant 4, 6, and 12 month cycles with the waste in this resort community varying by as much as a factor of two within a given year. Even within a given week, assuming multiple collections, the day of collection will impact the amount of waste (e.g. on a Monday/Thursday biweekly collection the heavier load will typically come after the weekend). This leads the decision maker to the serious issue of what level of waste production to design the districts for; or whether a single level can even be chosen.

One policy would be to design for the maximum anticipated load, but this could result in crews spending much of the year idle. As with most expensive services, one chooses a design level less than the maximum trading off other considerations in arriving at an equitable and efficient level. An initial impression is that one would desire as much flexibility as possible in matching manpower and equipment to the task at hand. Clearly, employees and trucks cannot be added or deleted freely: however, some services have worked arrangements supplying additional manpower during heavy periods from department of public works or other companion agencies. This time sharing enables better utilization of the workforce. Two methods may be used, a dynamic or a static approach: the former would employ additional workers only when the demand necessitated (in this case the other work would be preempted), the later would anticipate heavy work periods and preassign additional workers specifically on the basis of historical operational characteristics. There is essentially limited flexibility in changing routes -- the public anticipates collection on a prespecified day and acts accordingly, the crews can only be familiar with a limited number of route plans, and for managerial tractability, the route patterns should be relatively stable. Only a static reassignment program changing routes at most a few times a year seems both justifiable and operational. Briefly, under such an approach, several districting plans would be generated based upon different and purportedly characteristic design loads. The workforce would be modified to service accordingly: for public conveniance, one expects that the collection would remain on the same day for each area and at the same frequency. Given limited flexibility, higher service schemes might be initiated by the dispatcher for holiday, inclement weather, or other extraordinary heavy loads.

The more sophisticated approach of choosing several operating levels is highly system dependent. The actual methodology for predicting waste is identical, whether a single or many design

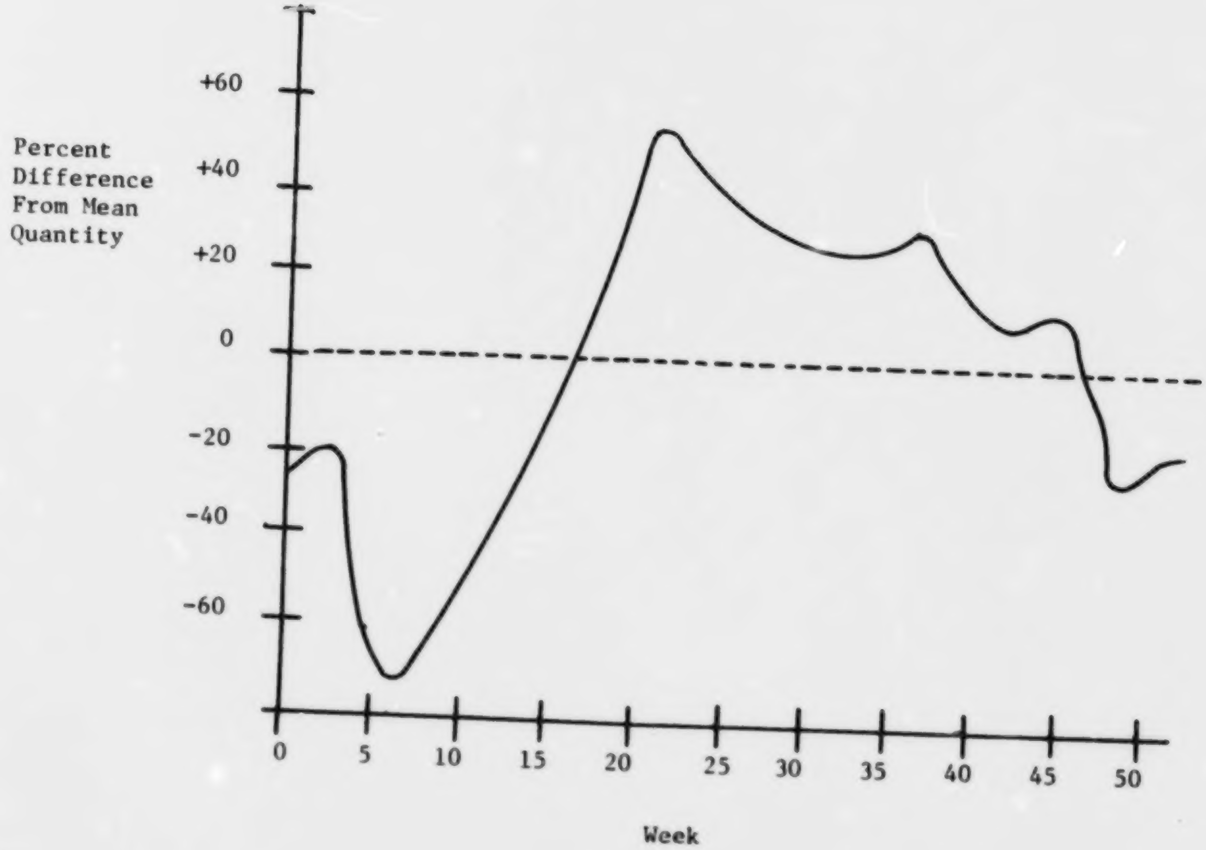


Figure 7.1: Weekly Waste Generation from Single Community

levels are chosen. This chapter focuses on the kernal of the problem. A decision must be made choosing at least a single operation level for the system. This level intimately depends on overtime policies, the undesirability of uncollected wastes, the normal utilization of the workforce that is desired, and the anticipated variability of waste load. The operating point chosen says that on average, x% of the time the workload should exceed this desired norm. Figure 7.2 showing a postulated daily town waste load with a chosen operating capacity depicts the situation. The ratio of crosshatched to total area represents the fraction of time that, on average, an overrun is anticipated.

Given that the decision maker has chosen a design level, the next step is to develop a prediction representative of the level chosen. In the example, days 240 to 320 might typically have loads of the magnitude desired by the decision maker. Some cross section for sampling, either chosen formally, by assessing a year's daily waste loads, or by intuition, is established as the first step towards developing the model for waste generation.

7.3 Aggregation

In the last section, data on subareas sufficiently small for districting was mentioned. There is in fact a severe tradeoff between the refinement of districts and cost-comptability. To get relatively uniform sized districts, small units must be input to the districting program. One can easily see this intuitively -- if the subunits averaged one-third the size of the desired districts and had large load variance, then one could expect districts for which addition of another unit might result in a significant overage, but for which only two units resulted in a severe underage. A variation of 40% from the mean desired workload represents over 3 hours of work disparity -- clearly an intolerable situation. However, as the number of units increases, the optimal districting schemes breakdown due to cost (see chapter 5.2). Fortunately, the heuristics can be adapted to start with a large number of subareas.

The waste is generated by individual, usually independent households. One might attempt to model on this level, but no data is available; at that disaggregate a level extensive data collection appears infeasible. The next logical level is the blockface. A blockface, as the name implies, is defined as a single side of the street between a given two intersections along that street segment (see Figure 7.3). Reviewing the collection mechanism, one sees trucks traversing arcs to service the individual collection points. Intuitively, collection of all points along a single arc segment by a single truck will be more efficient than multiple servers traversing the same arc. Note that in actual districting,

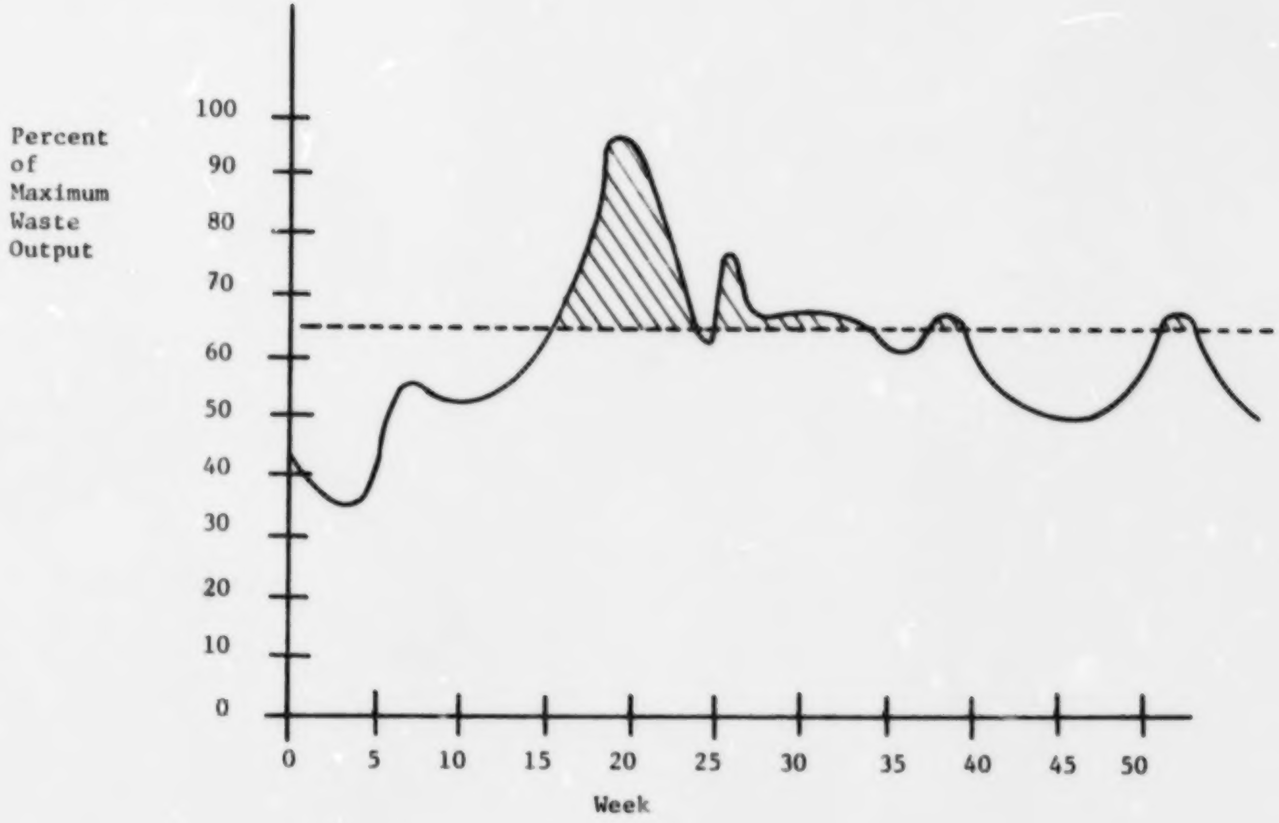
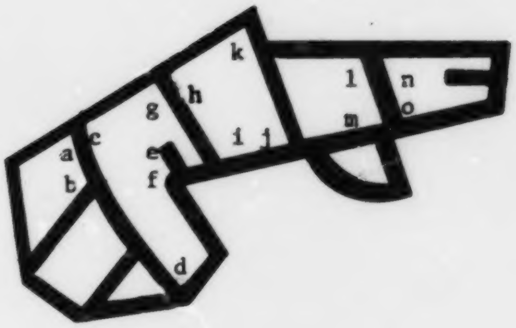


Figure 7.2: Choosing an Operating Point



$\overline{ab}$, $\overline{cd}$, $\overline{ef}$, $\overline{eg}$ are all sample blockfaces

$\overline{hijk}$ is a sample block

$\overline{lm}$ and $\overline{no}$ denote different blockfaces

Figure 7.3: Blockface Definitions

if both sides can be collected with a single pass, then the two blockfaces should be represented as a single demand point. Certain areas, due to traffic and safety considerations or system policy, can only have a single side collected at nay given time: here representation for districting is as two separate segments.

Data on the blockface level would be the most desirable with respect to flexibility from a districting viewpoint. At this juncture, however, such data is not generally available and the planner is forced to resort to the next higher level of aggregation, the census block. Dealing with data on either aggregate level can lead to certain statistical fallacies. The information is aggregated over an entire block, so that some variance within the block sample is lost. The causal assumptions and mechanisms we draw upon operate on the disaggregate household level. The potential pitfall known as the ecological fallacy obtains from inferring individual behavior from group behavior (32).

To validate the project approach, one must demonstrate that blocks are relatively homogeneous, that there is little variance in the individual household characteristics across the block. This is an area for future work and necessitates data on the individual household level to verify the assumption. Intuitively, the assumption of homogeneity seems reasonable. Further, once predictions are made, several blocks are aggregated into a collection district and normally leads us to expect a diminishing of any error (assuming no bias). The advantages of using census data, the availability, ease of updating, and accuracy seem to warrant using this information until more appropriate data may be found.

7.4 Underlying Theory Proposed

Econometric models cannot simply be fabricated on the basis of statistical correlation. In this project, the model sought is predictive: given a causal form and having calibrated the model, the anticipated output is a prediction of waste loads. A descriptive model in which historical implications are sufficient cannot be trusted to predict when confronted with significantly varied input: a causal model retains this ability.

Once an econometric model has been developed, it must, in some fashion be validated. The most common approaches include:

- statistical measures
- appeal to underlying theory
- field testing

Indeed, it is unlikely that a workable model can be developed without some theoretical basis for its formulation. This section postulates causal models for solid waste production and subsequent collection times.

One expects four basic factors to impact the solid waste generated by an individual household. These are:

- population
- dwelling unit size and character
- income level
- cultural characteristics

Intuitively households may be viewed as individual producers: one will likely not change his waste output as a result of that of his neighbors. Consumption in a non-agrarian environment is the basic symptom of solid waste production. As population increases, one expects that the total consumption for that given group increases and accordingly waste production increases. The amount consumed and then disposed of is also reflected by the size and character of the dwelling unit. Typically one expects that larger dwelling units or those in more private buildings (i.e. single family homes instead of large apartments) would be indicative of more waste production. Larger dwelling units require more material consumption. Income effects have seperate impact but also are reflected by the nature of the dwelling unit. Surrogate factors may receive explanation by descriptors with high correlation (e.g. single family homes to predict lawn waste). Finally, in somewhat of a catchall, is the concept of life cycle stage (3). This encompasses the set of factors which are not accounted for elsewhere. These factors embody the political and habitual patterns that influence waste generation. For example, a retired couple in an apartment would likely produce far less waste than a couple of students sharing an apartment; a family with two preschoolers far more waste than a family with two highschoolers. The stages described by Aldana (3) are given in table 7.1, who gives a detailed discussion of the segmentation of households for travel demand prediction.

The project modelling effort will build from census variables into models accounting for these four causal factors. Similar approaches are very scarce; one example of note is an excellent study by Jack Betz dealing with a predictive model for Los Angeles. A second approach by Boyd and Hawkins attempts to build a predictive model based exclusively on consumption patterns. There is little doubt but that if one knew the food expenditures, expenditures for durables, description of newspaper subscribers, etc., then prediction of waste generation with a sound causal basis could follow. Quon, Charnes, and Tanaka note in their work (106) that there is some demand supply interaction, that is, waste generation depends upon the frequency of collection. The models to be developed assume that the causal factors underlying this phenomenon are psychological and can be accounted for by calibration within the community of interest. This, of course, reduces their applicability to planning analysis.

1. Young, male bachelors
2. Young, female bachelors
3. Young, childless couples
4. Couples with children under 5 years of age
5. Couples with children in age bracket 5 to 14
6. Couples with children 15 years of age or older
7. Incomplete family - male head
8. Incomplete family - female head
9. Old, childless couples
10. Single, old males
11. Single, old females

Table 7.1: Aldana - Life Cycle Stages

Aside from these few earlier efforts, no other work was uncovered in this field of predicting residential wastes. The extensions to industrial of commercial wastes are straightforward, reflecting issues such as number of employees, type of activity, or sales.

The second phase, predicting actual collection time, has received more attention especially relative to technological advances such as one-man trucks, the influence of plastic bags on collection speed, or even exotica like satellite collection vehicles. Although a variety of innovations have been proposed, the preponderance of systems in the United States still operate with 10 to 40 yard rear loading packers and a crew of two or three. European systems have demonstrated more resourcefulness in developing alternative collection schemes. Yet over 70% of American communities still receive backyard pick-up: the collection mechanisms are beginning to diversify and one anticipates a continuation of this trend.

Consider a causal structure for explanation of the variation in collection times: total collection has two clearcut components:

- Actual pickup time
- Time required to haul to disposal point

One model developed for districting depends only upon collection time, with the goal of equalizing this quantity. Assuming equivalent equipment for all districts, the frequency of haul to the dump would be about the same for all districts. Therefore, the only differences in haul may be accounted for by distance from the point where the truck is filled to the disposal point. One assumption might be that on the same collection day district assignments will be compact and contiguous - that the variance in travel distance will be insignificant relative to the total haul distance to the disposal site. A more sophisticated approach would be to estimate haul times from every given block, and then to estimate the probability that the haul will be made from that block. This probability would simply be the fraction of total desired district load that the block contained. More sophisticated approaches might be taken. However, consider now only the actual collection time componant of this model, and discount the effects of haul time.

The actual collection time divides into four factors, the times due to:

- vehicle travel on line haul
- collector travel to pick-up point
- actual waste transfer operations
- miscellary including 'wasted' time and errors

Consider each of the major componants separately. Time due to vehicle travel obtains from:

- distance to be travelled
- effective velocity, itself a function of waste density
- topography

Travel time from the truck to pickup point depends upon

- expected distance between point of pickup and truck
- means of travel (usually walking) and method of carting waste

The actual time required to collect waste and dispose into the truck depends upon:

- number of parcels to be collected at each point, weight, and volume of these parcels, i.e. the total waste
- collection density fatigue factors
- queuing considerations at the truck

Clearly, as required travel increases, the time required for collection also increases. Similarly, travel speed is influenced by the number of starts and stops, weather, or posted limits so these factors also impact collection time. Finally, as the number of parcels increases, more handling is required: as weights or volumes increase, fatigue factors impinge; more frequent trips to the truck are required.

Although not comprehensive, these causal models derived from work cited provide a basis for formulating econometric models. The causality is not simply uncovered from the correlative, but rather is postulated from perceptions of the way the system operates.

7.5 Proposed Models Using Census Data

Now that a causal model has been proposed, and that the general character of the data has been described, the next step is to develop specific models which embody the causality. To this end, models for both waste output and anticipated collection time will be developed which use first published census data alone, and then census data which is available from both published and supplemental data available on computer output tape. The expanded data set is preferred because of the additional explanatory variables available. Tape data includes all of the published files and is available for all blocks for which the corresponding published data is available. A distinction is made only for the following reasons. First, certain planners might choose or be unable to use computer facilities. Most of the project work is designed for implementation with computer capability: however, for flexibility some models are amenable to hand calculations. The limited capacity of manual approaches makes them exceedingly undesirable, but using them is by no means impossible.

Second, the census data is in some instances incomplete due to misplaced information, unanswered forms, or deliberate supression to protect the privacy of individuals on certain blocks where disclosure would result in indiscrete public availability of an individual's circumstances. Therefore, models should be developed to employ limited data sets when none other are available.

7.6 Models for Waste Generation:

The data from census block statistic tapes includes the following information. Variable names are listed in the righthand column. The parameters included only in the published data have the corresponding variable name enclosed in parentheses. Variables that are indicators or population or lifestyle only include:

population	(POP)
elderly - % over 62 years	(ELDLY)
youth - % under 18 years	(YOUTH)
nonwhite - percentage	(NONWH)

Indicators of housing characteristics include:

total number of dwelling units on the block	(DUTOT)
total single unit dwellings	DU1
total units at addresses containing 2-4 units. (e.g. a duplex)	DU24
total units at addresses containing 5-9 units	DU59
total units at addresses with 10 or more units	DU10
total units with 1 or 2 rooms	RM12
total units with 3-5 rooms	RM35
total units with 6 or more rooms	RM6

Those of income include:

total number of rented units	(RENTED)
total number of owned units	(OWNED)
average estimated monthly contract rent	(AVRENT)
average estimated home valuation	(AVVALUE)

All values are aggregate for the given census block under consideration. Census blocks are readily referenced by a tract number and a block number: maps are available.

A linear additive form for the model, namely

$$y = a_1x_1 + a_2x_2 + \dots a_nx_n \qquad (7.1)$$

is postulated as the underlying causal assumption. That is, population, income, housing, and lifestyle characteristics all act independently in influencing the waste production. The linear additive form is depicted as figure (a) in contrast to the independent multiplicative form of (b).

(a) $x_1 \longrightarrow y \longleftarrow x_2$

(b)
$$\begin{tikzcd} x_1 \arrow[dr] & \\ & y \\ x_2 \arrow[ur] & \end{tikzcd}$$

Therefore, in developing sets of parameters for prediction, inherently independent parameter sets must be chosen.

Consider a first class of models which are primarily based upon the implications of representing relative population and life cycle measures by the inclusion of all dwelling unit classes. In addition, income effects are to be included directly. The complete model is of the form:

$$GALS = a*IL + b*IM + d*DU1 + e*DU24 + f*DU59 + g*DU10 + c \qquad (7.2)$$

where
GALS = total uncompacted gallons of waste produced

and where the AVVALUE and AVRENT statistics have been further aggregated into indicator variables. Essentially, income classes can be defined for the town under consideration and a 0-1 variable introduced such that:

IK = 1 if block under consideration is a member of income class K
0 otherwise

Define membership on the basis of the dominant residence mode for the block under consideration. This is a decision variable as are the actual breakpoints for the different income levels. Specifically, if the dominant type is rented then let IK equal 1 only if

$$L_k \leq AVRENT \leq U_k$$

where U_k and L_k are upper and lower bounds for the income class. Similarly for ownership as dominant, IK equals 1 only if

$$L_k \leq AVVALUE \leq U_k$$

An income indicator in the form as chosen essentially adds a constant amount of waste to the block when in fact the indicator is on. The assumption is that an additional small income increment will not result in additional spending due to inelasticity.

The four dwelling unit componants of equation (7.2) act as surrogate for population. Generally there is a very high correlation between total dwelling units and population: when performing ordinary least squares regression this co-linearity or dependence results in correlated error terms and therefore invalidate the parameter estimates. If no income data is available, a straight run with dwelling units and a constant might explain nearly as much of the data variance. That is,

$$GALS = a*DU1 + b*DU24 + d*DU59 + e*DU10 + c \qquad (7.3)$$

Intuitively, some income effect enters in the dwelling unit character. Finally, if the tape data is unavailable, one data point which almost always appears in the census data is the total number of dwelling units. The simple model of

$$GALS = a*DUTOT + c \qquad (7.4)$$

can almost always be run from census data. If, for some reason, the information is not published, it may be readily obtained from field observations (ie mail box survey, counting doorbells, etc.)

A second class of models attempts to incorporate lifestyle more explicity. The most general of these forms may be represented

$$GALS = a*ELDLYT + b*YOUTHT + d*IL + e*IM + f*DU1 + gDU24 + h*DU59 + i*DU10 + c \qquad (7.5)$$

Age acts as a surrogate for lifestyle. The income and population considerations are the same as before. This model may be extended to include a nonwhite population factor if historical data bears out the need for such an explanatory variable.

Finally, a third class of models for predicting waste generation is postulated. Here rental or ownership are surrogates for lifestyle, population, and income factors. The equation of interest is

$$GALS = a*RENTED + b*OWNED + c \qquad (7.6)$$

Note that both (7.4) and (7.6) are available exclusively from published census data. All models include a constant: the explanation for this variable is reserved for the next chapter.

7.7 Models for Predicting Collection Time

Although a relatively sophisticated causal model for determining collection time was developed, the actual models which can be constructed are somewhat less complex. Additionally, waste generated is output on a block level: ideally collection time should be output on a segment level. Assuming that the waste generated will be one necessary explanatory variable, then expected collection time must be output for an entire block perimeter unless the block can be considered sufficiently homogenous that the blockface waste data may be desaggregated from the entire block data. In the project work, this hypothesis was not tested, and therefore the time was generated on a block level. However, to retain generality, both approaches will be examined in this section of the report. Note, in contrast, that the causal assumptions and models for predicting waste generation are identical for the block and for the blockface approach.

To generate collection time on a blockface level, one additional fact enters into the model: that is, that the collection time required to traverse and service both sides of the same block is not the same as the sum of the service times for the two blockfaces. The issue of whether a single or double sided collection is used is a decision variable. Certain lightly trafficked streets or narrow streets are amenable to double side collection in a single pass; streets with much traffic or conditions otherwise presenting an obstacle or hazard to the collection crew should be serviced in two separate passes. Additionally, one way streets should be serviced in the proper direction. To calibrate the blockface model proposed, data would have to be collected on that disaggregate level. One possible model is:

$$TIME = a*GALS + b*DIST + d*BOTH + c \tag{7.7}$$

where the variables are defined

TIME - time required to collect the blockface (or block, depending on context)
DIST - length of street segment (or block perimeter)
BOTH - 1 if collection is on both sides simultaneously
0 otherwise

The influence of waste type and quantity are embodied in the number of gallons (uncompacted) as output from the earlier section. Uncompacted gallons are used as a measure because varying equipment compaction ratios can be used to translate into truckloads. Both sided collection and distance of truck travel are indicated directly in the equation. Distance accounts for travel time and gives some indication of waste density: both sided collection is self explanatory. The causal assumptions that do not enter are distance travelled by collection crews to and from the actual pickup points, topography, number of parcels collected, and character of the containers collected. These factors enter indirectly in the model calibration, and are contained somewhat in the constant.

The corresponding block based model ignores the implications of collecting on both sides and deals with the perimeter of a single block. The variable names defined earlier are maintained for simplicity. Time required is for an entire block collection and the assumption that the aggregate measure will suffice for districting to achieve equal workload. The equation of this form appears:

$$TIME = a*GALS + b*DIST + c \qquad (7.8)$$

In order to test the assumption that the block based measure is adequate, the next chapter will compare models (7.7) and (7.8) by using segment data.

7.8 Desirable Census Data

Having developed census based models, the deficiencies of this data are more obvious. Especially important for developing inexpensive and accurate models for public service operations are blockface based data. The need for such data desaggregation manifests itself in the models developed herein. Data on such a level would also be of use in school bus routing, mail delivery, deciding on preventive police patrol priorities, and a plethora of service operations requiring the server to traverse or base decisions upon individual street segments. Present upward data aggregation may no longer be valid for the contemporary urban environment: census data could easily serve as a decision making tool.

Specifically, regardless of whether the data is released in a more disaggregate form, certain additional information could benefit the present modelling effort. The concept of a life cycle indicator doubtless has great impact upon consumption and disposal habits. Census forms should in some way reflect this: aggregate under 18 years or over 62 years is insufficient in ascertaining the nature of a block or blockface. Lifestyle information is important in determining consumption, educational, welfare, medical, or vocational service requirements. Block based lifestyle information would aid in the location of schools, hospitals, ambulances, counselling centers, and so forth. Finally, as an adjunct to the existing census data, more specific information should be kept on income and property holdings.

7.9 Transferrability issues

The basic form of waste and collection time prediction models has been presented. The actual methodology for utilizing these tools will be outlined in this section. Essentially, two approaches are postulated: the models may be tried and calibrated for each community under consideration or an exhaustive catalogue of models could be developed and available for reference.

Ordinary least squares regression techniques take a set of data and fit a function to estimate the desired parameter. In the models considered, waste in gallons or time in minutes as dependent variables are predicted against a set of independent variables. Uncompacted gallons are used as a measure because of transferrability to different equipment with varying compaction ratios. One full set of all parameters must be known to calibrate the coefficients. The issue that rises is how large must this set of data be to obtain an estimate in which one has confidence.

This entails sampling and recalibration for each community. The advantages immediately apparent are:

- existing model structures can be utilized
- system intangeables (morale, etc.) are included implicitly
- operational considerations (i.e. lawn trimmings) are included.

The resultant model should be relatively accurate dependent upon the success and character of data gathering. Specifically, data should be gathered by sampling selected areas of the town for several weeks around a period historically close to the chosen system operating point. The output sought is a "thick" cross section, a cross sectional data base in which daily or weekly stochastic variations have been minimized. No simple rule of thumb can be given for choosing the data base size or the area it covers. This depends intimately upon the homogeneity of the region for prediction: suffice it to say, under fairly general assumptions as the sample size increases, the expected standard deviation decreases as the square root of the sample size.

Areas to be sampled, rather than random, should be carefully assessed to incorporate the diversity evident within the collection area. An analysis of this sort using latin square techniques may be seen in the study by Betz (11). Briefly, this technique chooses the independent input factors outlined in the causal model and attemps to select points for sampling so that a minimum of sample points are required to investigate the important factors.

The disadvantage of individual model calibration is that it requires data gathering and statistical analysis each time the methodology is applied. Data collection entails considerable expense, and requires trained personnel and data handling capacity. The whole area for which a model predicts must be chosen for relative homogeneity. For example, Co-op city in New York could not be analyzed with the surrounding neighborhood to obtain meaningful results. Also, the districting programs such as REDIST only work economically with 2500 or fewer starting blocks. However, the ease with which this methodology may be applied as compared to exhaustive sampling makes it a relatively attractive alternative.

The second alternative is to classify communities by certain general characteristics (i.e. population, mean income, mean dwelling units per block,average rented units per block, etc. all falling into a predefined class or range) and to have a lookup table by community type containing a precalibrated model with relevent coefficients. In this instance data gathering and processing would be eliminated.

At a glance, too little work has been done in community classification of this sort. Further, many parameters characterize a community and achieving the specificity necessary for solid waste prediction might entail too much a priori modelling. The implicit seasonal and environmental factors could not effectively enter into an exhaustive model. The causal theory on which these models are founded seems adequate: perhaps the best approach would be to develop calibrated versions on an experimental basis and then to retroactively classify communities and establish a compendium community typing ex post facto.

7.10 Future Extensions

This chapter outlining the theory and methodology of building predictive waste generation and collection time models has opened up several areas for extension and future research. Naturally, more questions will arise as implementation and feedback ensue.

The first priority of future work is to develop models which predict waste generation on the household level rather than the aggregate. The steps involved include definition of a causal basis, establishment of an appropriate data base, and finally testing of the model developed. Tied up with this question is that of data availability, both for developing the concepts and for actually applying the model to real work problems. The feasibility of such application must receive careful assessment before work is carried very far.

Data modification and improvement, as discussed earlier, must also be undertaken. To reiterate, data requirements are such that

- blockface based data
- life cycle indicators
- efficient updating techniques

would all expedite present modelling efforts. One interesting possibility would be to predict blockface characteristics from a block model (see section 5.4).

Seasonal variations and the whole issue of choosing operating points must be addressed. What causes seasonal variations? What causes variations within a given week? What effect does collection frequency have upon waste output? How can the effect of other service changes such as recycling programs be estimated? What variations in collection and traveltimes are caused by weather? How can the causality in the gallons time models be better implemented?

Finally, commercial and industrial loading, separability, and predictability need attention. Two important questions are: How do the seasonal and other variations affect waste producers and what impact do commercial establishments have upon waste collection times. Better data sources are especially critical in this realm, where business turnover and growth are quite high. Special classes of separable and recyclable waste like computer output might be best served by separate collection and sale. The feasibility of commercial and industrial collection within the public collection domain must be established.

As the modelling capability for social systems becomes more sophisticated, gains may become possible in this portion of the attempt to build a comprehensive approach to solid waste collection. For example, little demand modelling (see reference) has been examined and used in practice; there is applicability to this waste prediction problem. The entire prediction question is still open. If efficient data gathering techniques (for example, introducing tracers into packages) are developed, prediction might be on the basis of direct survey. Also, the accuracy of the predictions might be varied over a relatively wide range and good results easily obtained from adjusting districting boundaries after a rough plan had been developed. The prediction techniques developed here will hopefully suggest some methods for future analysis.

THE BROOKLINE EXAMPLE

This section describes an application of the econometric models developed in the previous chapter to waste collection in the town of Brookline, Massachusetts. Both time and wasteload estimates were developed, and districting plans generated from these estimates. The chapter describes the character of the system, some difficulties encountered in data processing, the waste generation models and the districting outputs. The work is presented as exemplary of the type of effort necessary to implement the proposed methodology and not as a practical districting exercise.

8.1 A Prototype Analysis

Several reasons motivate the development of a prototype analysis within the project. The primary reason was validation of the work to date--do the models yield reasonable results or are there obvious omissions? Ideally, one would choose to apply the analysis and then to perform an actual field test to compare results with the present operating system characteristics. New proposals could be implemented and a multiattributed utility assessment such as that performed by Keeney and Ellis (37) could be used to choose between alternatives. Relevant attributes might include cost, noise, fly population counts, and some aggregate conveniance measure. This approach yields no information as to how close the system is to some optimum. deNeufville proposes that for social systems the optimal region is a rather broad plateau and that several alternative forms will yield satisfactory results. (32). The issues of how good a system is and when one format is "better" than another need definition and investigation.

The availability of real world data facilitated limited validation of the models. More importantly, the encounter brought to light some of the difficulties in data collection and manipulation. Simple aids to analysis were developed and will be discussed in subsequent sections. Some of these aids may seem painfully obvious: ideally, however, the analysis performed herein can serve as a model to be made readily available to both internal analysts and consultants in solid waste collection. The goal is to provide a tractable result; to this end, the rationale and the mechanism should be clear to system managers, governmental decision makers, union personnel, and perhaps even the public who must approve and pay for the service. The system is too complex for a "Solid Waste Cookbook": potential pitfalls will be highlighted.

The work was designed to address problems faced by solid waste collection managers. Handling actual data gives some indication of the time required, sophistication, and approximate costs of performing such analysis for revision of collection activities. Computer capability and the necessary software packages will also be reviewed.

The town of Brookline, Massachusetts, was chosen for the prototype analysis for several reasons. Brookline (with whom we had previous contact) had negotiated a contract with the Sanitas Service Company to perform a comprehensive review and redesign of the town's solid waste management system. The exact approach and specific data available will be discussed in the next section. The town and Sanitas gave us some cooperation in allowing access to rough data.

Brookline is a residential suburb in Greater Boston with a population of about 60,000 people (see Figures 8.1-8.3). It lies to the west of Boston proper bordering on the neighborhoods of Roxbury, Brighton, and Jamaica Plain and on the town of Newton, Massachusetts. The northern and eastern sections, especially the area north of Beacon Street or east of Harvard Street are primarily apartments, including some moderately high rise buildings. The southern and western sections of town contain mostly single family homes including some with multi-acre lots. Accordingly, one sees a reasonable diversity in the character of the residence found in Brookline. In developing and testing the prediction models, this diversity was sought to assure that the underlying causality was captured, and that the validation did not simply consist of fortuitous correlations. In addition, one expects to see dramatic differences in district size with even a limited foreknowledge of block characteristics.

Commercial waste was not included in the prediction nor is most of it collected with the normal residential pickup. The businesses concentrated on Beacon, Harvard, or Boylston Streets are serviced by either private collection or on a fee basis from the town. Town collection of commercial establishments is primarily from dumpster boxes or rear alleys inaccessable with 20 yard packers. Therefore, an entirely separate subsystem handles this waste collection using piggyback trucks and a 10 yard alley cat packer. See Figure 6.3 for the location of demand points and the first year project report (60) for a more detailed discussion of this aspect. Using solely residential models in Brookline seems acceptable since the commercial subsystem is essentially

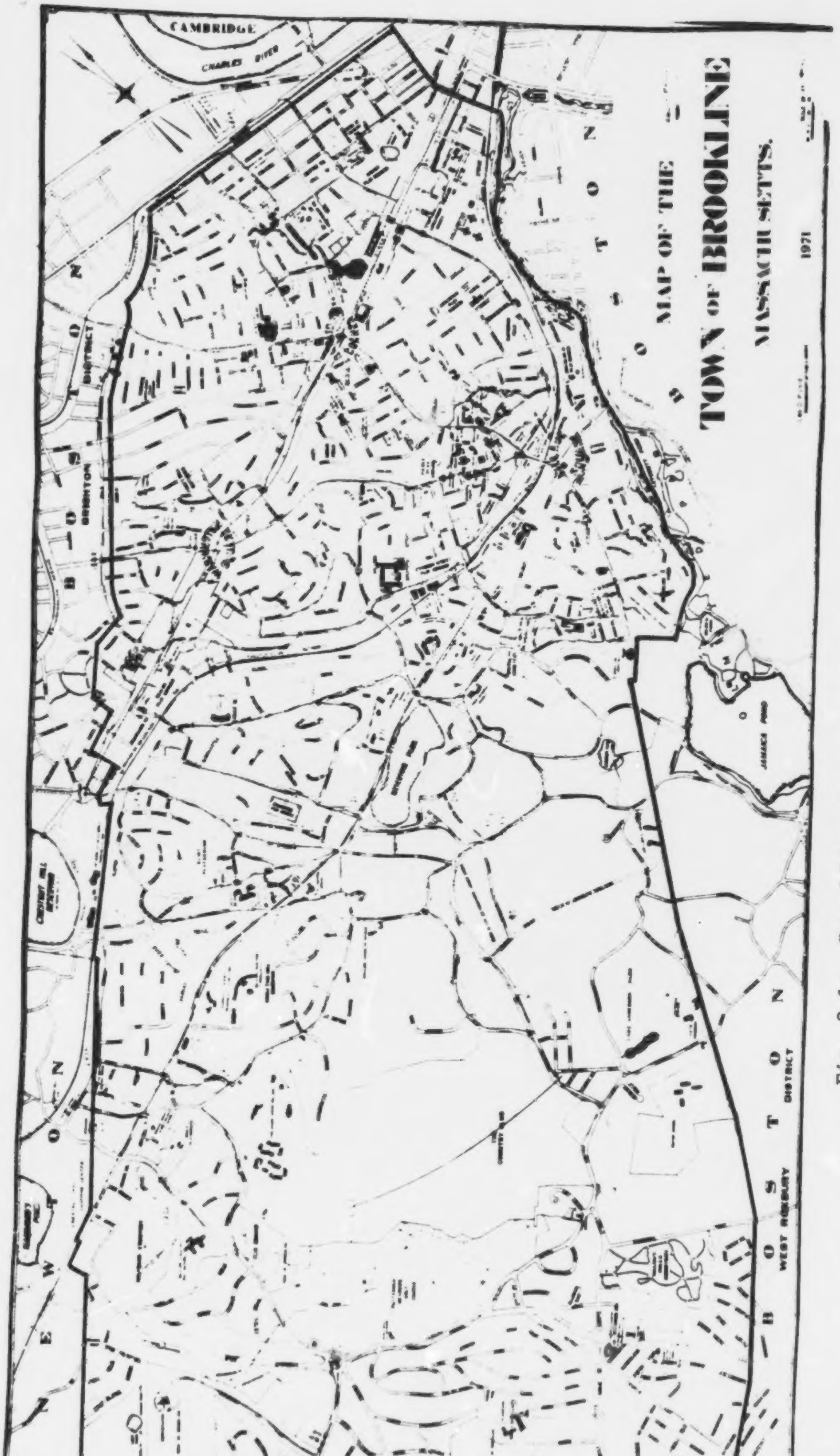

MAP OF THE
TOWN OF BROOKLINE
MASSACHUSETTS.
1971
CAMBRIDGE
CHARLES RIVER
BOSTON
BRIGHTON DISTRICT
JAMAICA POND
BOSTON
WEST ROXBURY DISTRICT
NEWTON

Fig. 8.1: Brookline Street Network

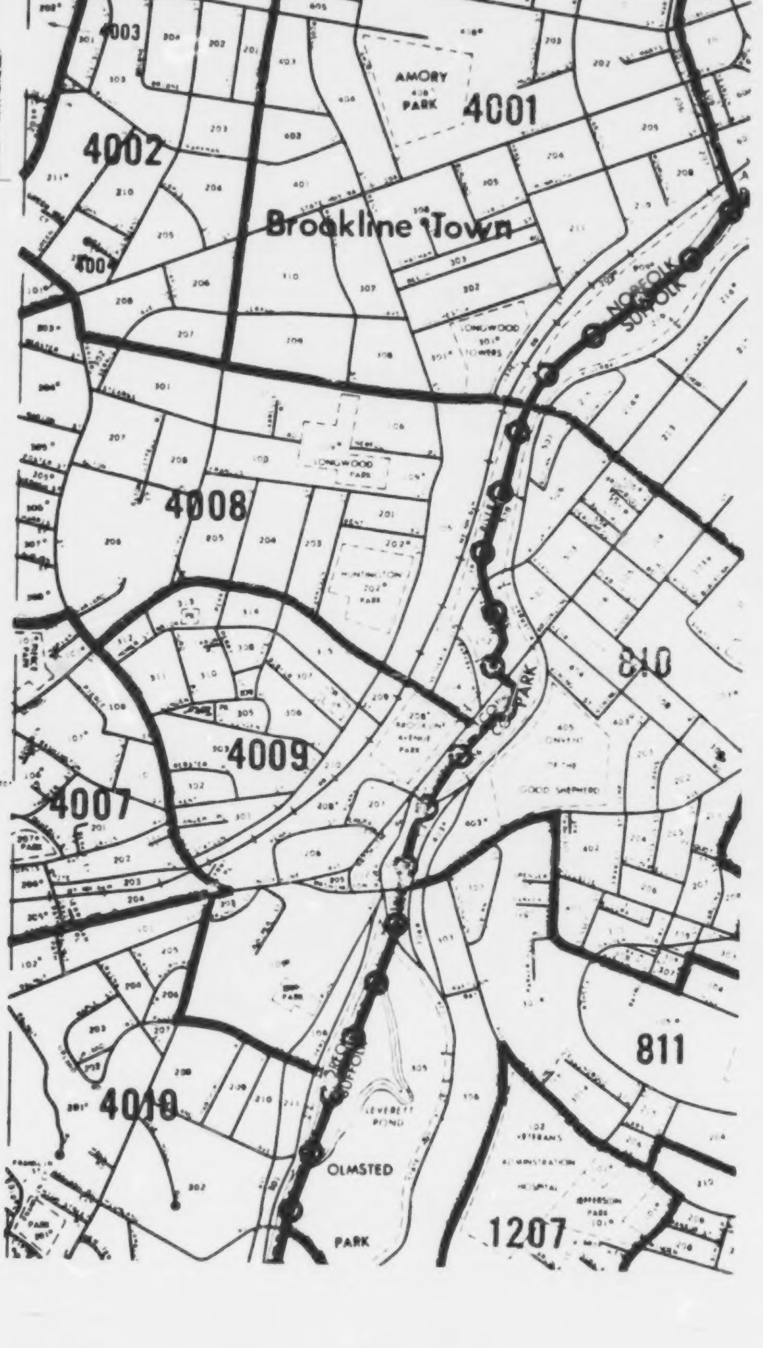

4003
4002
4001
AMORY PARK
Brookline Town
NORFOLK
SUFFOLK
LONGWOOD TOWERS
LONGWOOD PARK
4008
HUNTINGTON PARK
810
4009
4007
CONVENT OF THE GOOD SHEPHERD
811
4010
LEVERETT POND
OLMSTED PARK
VETERANS ADMINISTRATION HOSPITAL
1207

Fig.8.2: Brookline Census Block Map - North

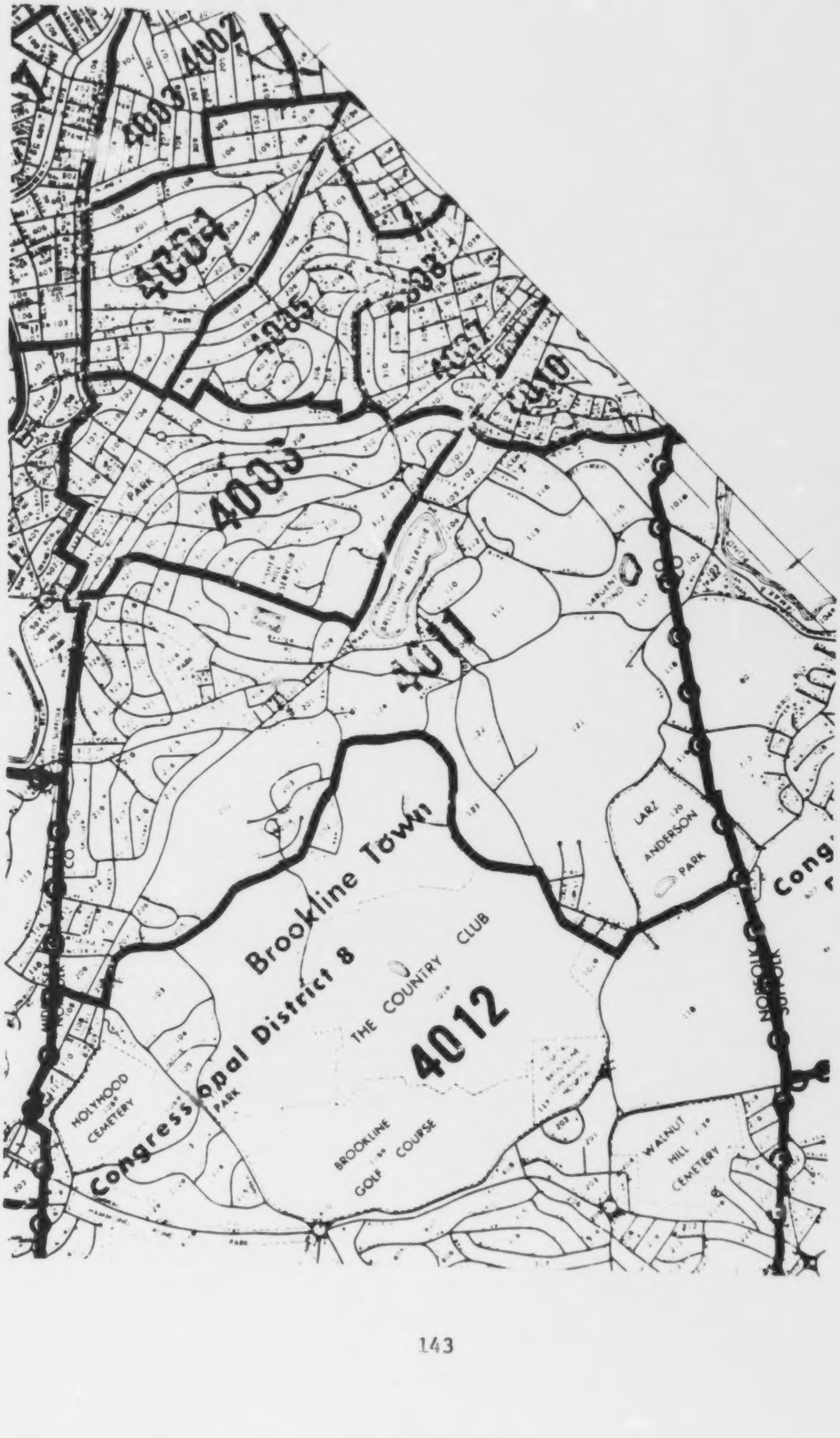

4002
4003
4004
4005
4007
4008
4009
4010
4011
4012
Brookline Town
Congressional District 8
THE COUNTRY CLUB
BROOKLINE GOLF COURSE
HOLYWOOD CEMETERY
WALNUT HILL CEMETERY
LARZ ANDERSON PARK
BROOKLINE RESERVOIR
SARGENT POND
NORFOLK
SUFFOLK
PARK
Cong.

Fig.8.3: Brookline Census Block Map - South

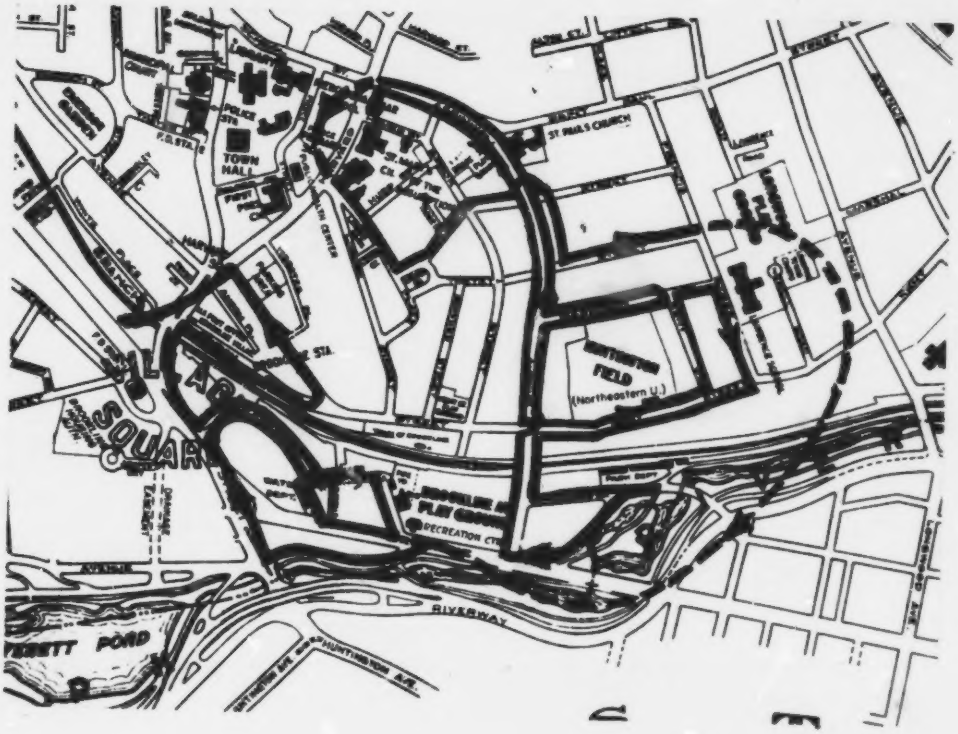
separate.

Collection of residential waste done as a service of the Department of Public Works (DPW) is financed out of the general property tax levy. In the town system of government, a town meeting decides on major policy matters and expenditures; a Board of Selectmen act as executers. This Board appoints the Director of the DPW, and the Assistant Directors for the various Divisions (Sanitation, or Highways, for example). The contract to Sanitas shows that the various policy-makers have an interest in innovation and change.

Nevertheless, the format for residential collection is simple. Collection is weekly from curbside using eight 20 yard packers; two spares cover breakdowns or heavy loads. There are 40 collection districts for a five day work week. Crews operate on a modified daily route system; if the collection is completed early, the crew can leave, and if not, the waste is left for the beginning of the next day or collected under overtime. Normally crews start at about 7:30 a.m. and finish by about 4:00 p.m. with an hour for lunch. Three person crews are the norm: workers borrowed from the DPW Highway Division staff spare packers for heavy loads.

The present districting is an evolutionary distillation of intuition and experience in system operation. This evolutionary rather than planned character is prevalent in many urban service operations. In the case of highly capitalized institutions, a hospital for example, it is difficult to redesign to meet changing demand. This is true also for a highway or fixed route transit line: these facilities exhibit the additional characteristic of creating or relocating demands (i.e. people tend to settle around them). The techniques developed herein facilitate updating collection districts and routes at regular intervals to meet changing demand patterns. In solid waste collection a new demand, say a small housing development, is often assigned to a distant but lightly burdened server. Travel time to and from this new demand point is totally waste d with respect to collection crews. Several actual Brookline districts as constructed from the Sanitas data exhibit this ex post facto redesign (see, for example, Figure 8.4). Although present Brookline routes appear fair, increased efficiency and capability for revision and update are added by rigorous analysis.

Garbage in Brookline may in the future be collected together with trash, but this is more a political than an analytical problem. All the waste is now burned in the town incinerator in the western corner of the town, census block 12-615. Paper and plastic collection bags used extensively within the town are not provided to


TOWN HALL
POLICE STA
ST PAULS CHURCH
FIELD
(Northeastern U.)
SQUARE
PLAY GROUND
RECREATION CTR
RIVERWAY
POND
HUNTINGTON AVE

The above traces the route of a single truck through a one day collection district. Note the lack of compactness.

Figure 8.4: Sample Brookline Route

residents due to budget limitations.

It was originally thought that the Sanitas study would be available for comparison with project output: this hope has not been realized. Fortunately, Bookline provided an excellent basis for a prototype--the authors' familiarity coupled with first-hand inspection gave insight into the operations. Brookline's diversity, reasonable size, separate residential collection, data availability, uniform equipment across the town, and convenience all contributed to the town's attractiveness for a demonstration analysis.

8.2 The Data

Data for the project came from several sources. The ultimate basis for prediction was the census as published (132) and the corresponding tape data. The models were calibrated with data taken from survey output from Boeing Computer Services to be processed for Sanitas. In addition, sources such as town maps and miscellany (like listings of one-way streets) were useful.

The type of census data necessary, as described in Section 7.6, was taken from both tape and published volumes. Recall that block level data is the lowest level of aggregation available from the census. Data was referenced by the census block and tract numbers. To maintain generality for districting, zero population and therefore zero waste blocks were included to result in complete division of the town. In total, there were 463 census blocks, 411 of which had residents. Dwelling unit data available for nearly all blocks was supplemented in the few instances of census errors with estimates taken from maps.

A description of the income indicator variables used may also be found in Section 7.6. In this specific case, low, medium and high income classes were chosen. The breakdown by income classes may be seen in Table 8.1 (a) for renters and 8.1(b) for owners. The actual bounds were chosen so that approximately one half of the blocks were middle income, and one quarter each the other classes. Establishing type dominance on a block was done somewhat arbitrarily. The dwelling unit category (rented or owned) with over 70% of the total block dwelling units dominated. Income is an important factor and improvements in the design of income surrogates are an area for more work.

For model calibration 103 census blocks were chosen based on the availability of Sanitas data. Census data was checked with visual

	Income Class	Var.	L_k*	U_k
(a)	Low Income	IL	---	\$100
	Medium Income	IM	\$100	\$230
	High Income	IH	\$230	---
(b)**	Low Income	IL	---	\$ 32
	Medium Income	IM	\$ 32	\$ 50
	High Income	IH	\$ 50	---

* L_k and U_k are the lower and upper limit respectively on either rental or home value for the k^{th} income class.

** In thousands of dollars.

Table 8.1: Income Class Characteristics

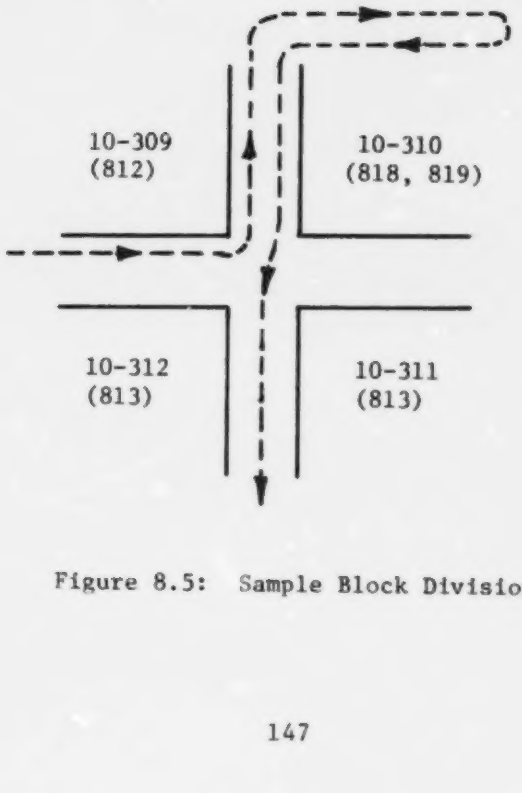
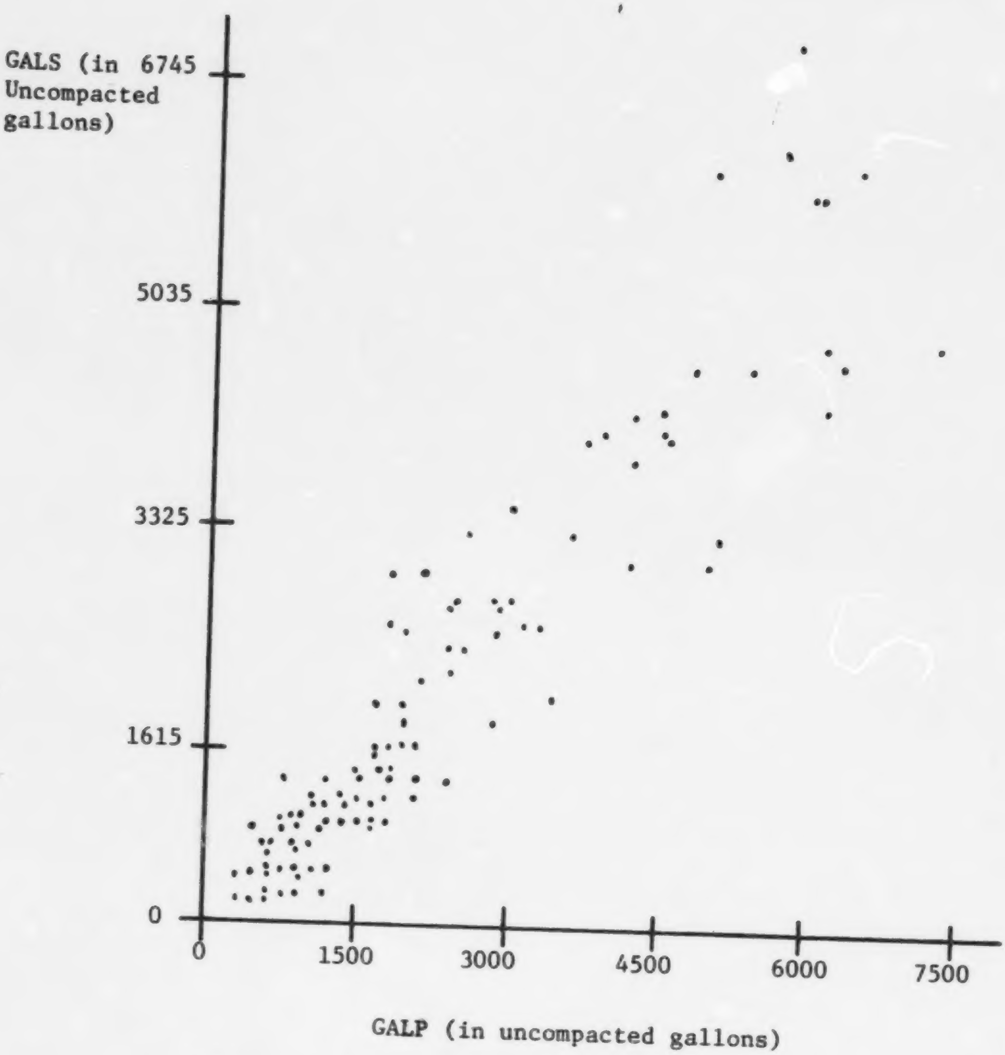

10-309
(812)
10-310
(818, 819)
10-312
(813)
10-311
(813)

Figure 8.5: Sample Block Division

inspection or comparison to a map; several blocks had completely unreasonable statistics as a result of processing errors and were discarded for calibration.

The data received from Sanitas was not collected for our study specifically. Sanitas subcontracted routing services to Boeing, who sent trained inspectors (two per route) to follow crews around on their daily routes--a comprehensive townwide data set resulted. Inspectors went in separate vehicles-- times were recorded by stopwatch, mileages by vehicle odometer. Data collected included segment name, number of houses (buildings), time to collect segment, numbers of cans, bags, boxes and bundles. Also included were a code indicating the direction of collection and dealing with the block characteristics based on zoning information.

Note first that the data was collected by street segments and not by blocks. The project team had to reconstruct routes on maps and assign waste to appropriate blocks from sequence numbers. This worked fine except for one class or segments which recorded waste in the aggregate as collected from both street sides (i.e., two different blocks). The issue that arose was how to assign this waste giving appropriate outputs to each side of the street. For example, in Figure 8.5 sequentially tracing the routes (indicated by arrow), the loads associated to data points labelled 812 or 819 would be assigned to blocks 10-309 or 10-310 respectively; however, data point 813 must be divided between 10-311 or 10-312 since it was recorded as a collection of both sides in a single pass. Two approaches might be chosen. One's intuition says, partition on the basis of population; however, with the ultimate goal to predict waste on the basis of population, that would add systematic bias to the sample. This yields an upper bound on the goodness of fit of the calibrated model assuming the validity of the causal assumptions. A second approach possible would be to divide the loads assigning a randomly drawn fraction to each block bordering on the segment in question. This totally unsystematic assignment should simply add variance and no bias to the sample and effectively result in a lower bound on the econometric model behavior. Both approaches were actually used in calibrating the prediction models. Figure 8.6 gives an indication of the effect of this action: gallons divided randomly for certain block segments (GALS) are plotted versus the gallons figured as a fraction of the population (GALP). In fact, the correlation between the two statistics, .96, is high as we would expect. The census and waste statistics are listed in Table 8.2. Variable definitions may be found in the previous chapter. These problems encountered were specific to the form of the data received. Clearly, if one went out to collect data explicitly for the purposes of calibration as described in Chapter 7, then the



This scatter plot shows predictions based upon population blockface division versus predictions based upon random blockface division.

Figure 8.6: Scatter Plot, GALP vs GALS.

Variable	Mean	Variance	Standard Deviation	Coeff. of Variation
POP	129.914	12974.4	113.905	0.876773
NONWHT	1.38628	6.77771	2.60340	1.94824
YOUTHT	24.9026	395.635	19.8906	0.798726
ELDLYT	31.1266	1621.32	40.2657	1.29361
DUTOT	50.0095	3082.86	55.5235	1.11026
DU1	11.2067	87.3128	9.34413	0.829361
DU24	15.5714	331.843	18.2166	1.16987
DU59	8.80852	257.925	16.0600	1.82303
DU10	10.6952	1161.50	34.0808	3.18654
RM12	4.05714	95.9390	9.79485	2.41422
RM35	24.7333	1819.97	42.6611	1.72484
OWNED	15.1619	117.656	10.8469	0.715408
AVVALUE	28.3409	461.020	21.4714	0.757610
RENTED	34.0000	2961.33	54.4181	1.60053
AVRENT	109.895	8250.17	90.8304	0.826518
GALS	2309.21	0.322841E 07	1796.78	0.778092
GALP	2282.43	0.351603E 07	1875.11	0.821541
GALAV	2303.80	0.317763E 07	1782.59	0.773761

Table 8.2: Sample and Population Statistics

input could ascribe waste outputs to coding by census blocks. Simple district maps to mark routes and forms listing block and tract numbers for assigning waste output are all that are needed by inspectors.

The data collected in numbers of parcels or containers would normally have as adjunct truckload weight data for each segment of the route collection. This data was withheld from us by Boeing: instead their estimates of parcel contents as regressed from the 40 district data points were used in the project analysis. These coefficients are listed: 28 gallons per full (fullness of on estimated by data collectors) can, 15 gallons per bag, 14 gallons per box, 19 gallons per bundle. Data gathering using simple counts is convenient; unfortunately a regression townwide to estimate the above coefficients assumes homogeneity in use of containers, i.e. a plastic trash bag in the suburbs is disposed of as full as one in an apartment complex. This assumtion may have resulted in bias being added to the sample. In the actual redesign of the analysis, a more sophisticated technique--perhaps an advance inspection team sampling individual parcels--should be used in calibrating the waste output statistics. Simple counts may be an unsatisfactory statistic and other measures sought: lacking this flexibility, the above coefficients translated from containers to uncompacted gallons wasteload apportioned to blocks. It would also be desirable to estimate weights per type of package for the analysis.

Graphical tools aided in manipulating and understanding the nature of the data. Large maps were cut up for use as route maps through the original districts. Others were coded with census block numbers and sequential collection references translated onto maps and indexed by census tract and block numbers. At this point, 103 blocks were chosen for which complete data had been obtained--these included some segments for which loads had been approtioned randomly. Figure 8.7 gives an indication of the locations of blocks used for calibration: fortuitously, they were scattered fairly randomly about town. For simple mechanical convenience, we recommend that towns get in the habit of referencing town blocks by census tract and block numbers, and that these numbers be printed on town maps.

Finally, maps served to determine contiguities, distances along the block perimeters, and the coordinates of block centers. The former was established by visual inspection. Distances were measured with a map wheel tracer to 5% accuracy. Block coordinates were measured from an arbitrary reference and the incinerator plotted to calculate haul distances. At this step, a simple digitizer would have greatly expedited data processing.

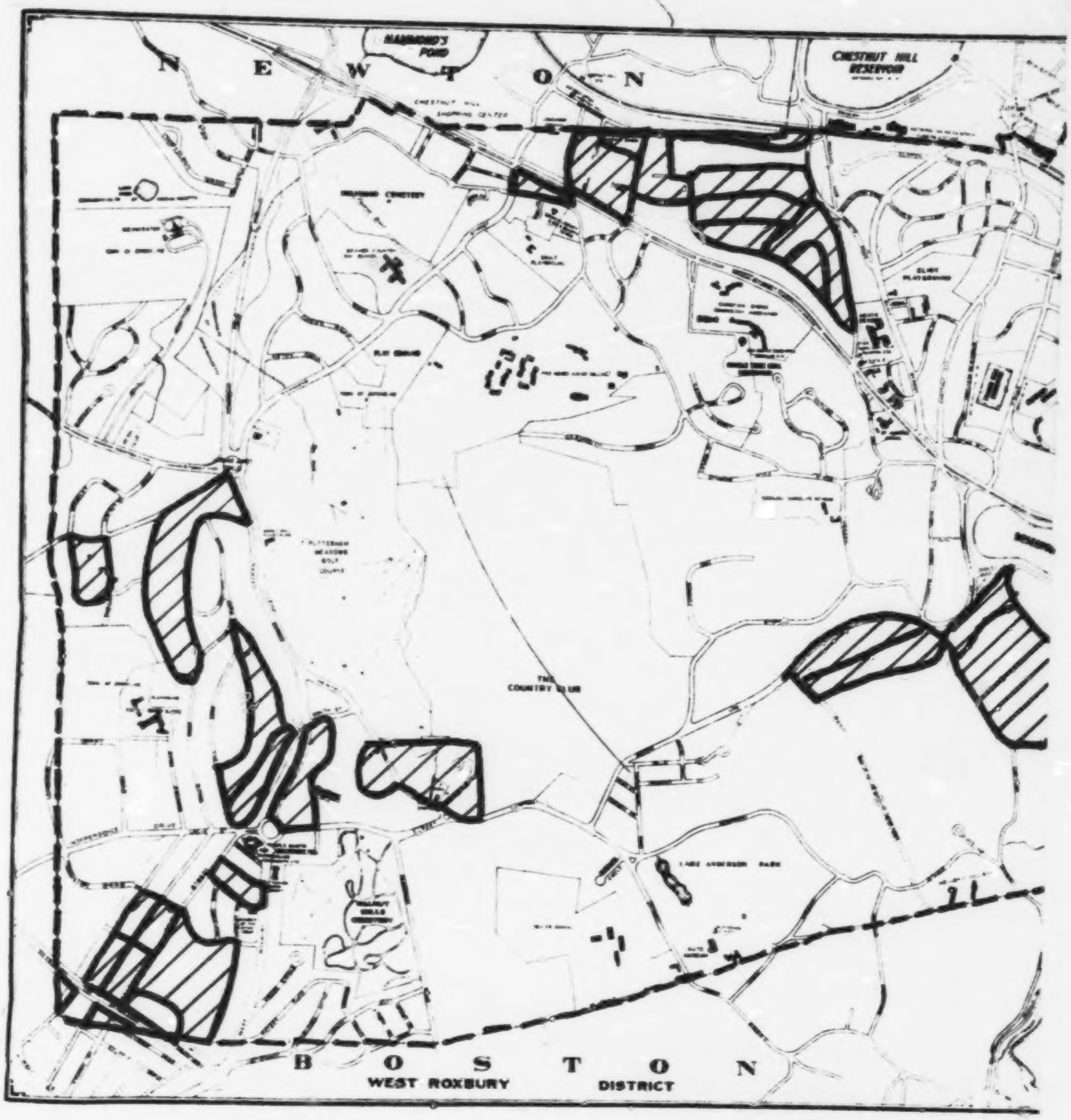

N E W T O N
HAMMOND'S POND
CHESTNUT HILL RESERVOIR
THE COUNTRY CLUB
B O S T O N
WEST ROXBURY
DISTRICT

Fig. 8.7: Blocks Used for Calibration

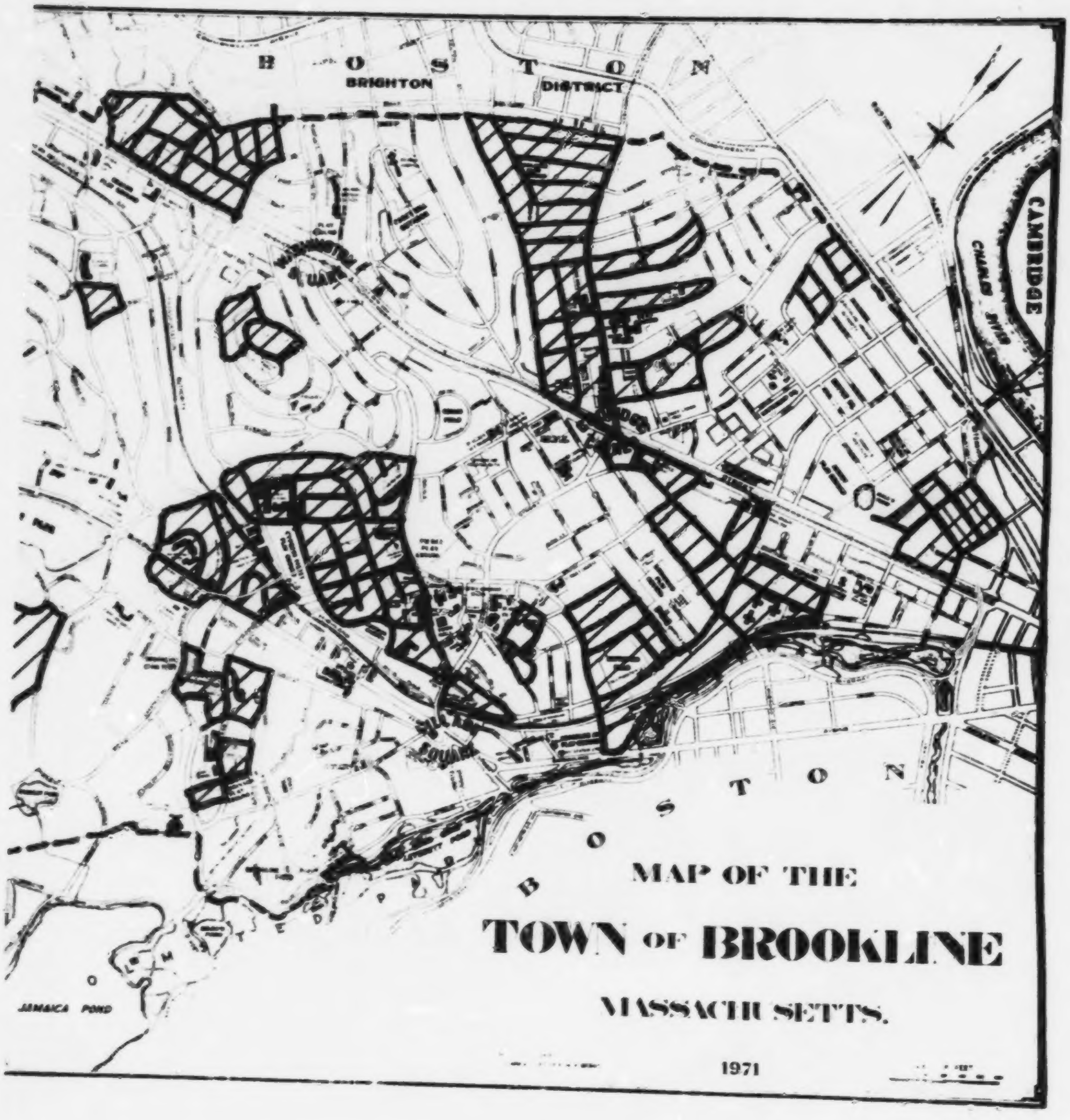

B O S T O N
BRIGHTON
DISTRICT
CAMBRIDGE
CHARLES RIVER
B O S T O N
MAP OF THE
TOWN OF BROOKLINE
MASSACHUSETTS.
1971
JAMAICA POND

Fig. 8.7 (Continued): Blocks Used for Calibration

8.3 Application of Waste Generation Models

Census and waste data processed into an appropriate form and units using simple FORTRAN programs were input to calibrate the models as described in Section 7.5. Recall that three classes of models were developed in that section, and that the models had provisions for backup in the case of data unavailability.

The assumptions under which the analysis was carried out include:

- homogeneity across an individual block
- relatively diverse sample for calibration
- no commercial or industrial loads
- dumpster loads handled separately
- waste per parcel has already been determined
- household is the causal level of significance
- input variables act independently.

These assumptions were developed in this and the previous chapter. The model for calibration was carefully chosen to, by and large, fulfill these criteria.

The first model sequence in order of preferred equations, hereafter termed WASTE I, consists of Equations 7.6 and 7.4. The second sequence, WASTE II, of Equations 7.2, 7.3, and 7.4. The third, WASTE III, includes Equations 7.5, 7.3, and 7.4. For convenience, the variables are charted in Table 8.3. The tabulation shows preferred sequence ordering and new equation numbers for convenience.

Important in assessing a model's validity are the statistical measures. The models should reasonably explain much of the variance of the data. Consider first the actual coefficient as determined by ordinary least squares regression. A package entitled the Economic Software Package (ESP) (111) developed for econometric work was used in this contract. A variety of other packages including TROLL, BMD , and SPSS perform similarly. Running on a system 370/165 the cost to the project of 103 point sample calibration runs was negligible. Table 8.4 includes the relevant coefficients obtained for the independent variables regressed against GALS (waste in uncompacted gallons where ambiguities disaggregated to the block level were decided by random division).

Consider each equation separately and observe how it matches the postulated causal model. For Equation I-1, rental tenants contribute less than owner tenants. Implicitly reflected here are income and living space differences--most owners live in single

Equation Sequence Number		Dependent Variable	Independent Variables
WASTE I	I-1	GALS	RENTED, OWNED, C
	I-2	GALS	DUTOT,C
WASTE II	II-L	GALS	IL, IM, DU1, DU24, DU50,C
	II-2	GALS	DU1, DU24, DU50, C
	II-3	GALS	DUTOT,C
WASTE III	III-1	GALS	ELDLYT, YOUTHT, IL, IM, DU1, DU24, DU50, C
	III-2	GALS	IL, IM, DU1, DU24, DU50,C
	III-3	GALS	DUTOT, C

Table 8.3: Equations of Interest

Equation Sequence Number		Independent Variables (Coefficients)
WASTE I	I-1	(13.9) RENTED, (41.6) OWNED, (1182.6)C
	I-2	(15.2) DUTOT, (1540.9)C
WASTE II	II-1	(619.3) IL, (655.2) IM, (35.0) DU1, (37.11)DU24, (8.5)DU50, (626.0)C
	II-2	(36.8) DU1, (41.4)DU24, (8.7)DU50, (1038.77)C
	II-3	---same as I-2---
WASTE III	III-1	(-20.3) ELDLYT, (-8.7)YOUTHT, (502.9)IL, (659.0)IM, (53.5)DU1, (58.3)DU24, (24.2)DU50 (671.3)C
	III-2	---same as II-1---
	III-3	---same as I-2---

Table 8.4: Calibrated Coefficients

family homes (the correlation between DU1 and OWNED is -.72, between DU1 and RENTED IS -.30 --these correlate well with middle and upper income blocks. In Brookline, elderly live primarily in rental units (the correlation between ELDLYT and RENTED is -.91) and this again matches the causal assumptions that elderly produce less waste. Townwide, elderly average roughly 25% of a given block population, so one expects this component to be significant. The second WASTE I equation simply reflects the relationship between total dwelling units and total waste production. The causality reflected here is that waste is generated by people in households (DUTOT correlates with POP as -.97)--dwelling units was chosen rather than population in modelling as to reflect the assumption that the individual household and not the individual is the level of interest in waste generation.

For WASTE II, Equation II-1, note first that units in buildings with two to four dwelling units contribute the most waste: single unit output matches this. Only the larger buildings with presumably smaller units reflects a marked difference in total waste output. Again, this coincides well with the causal assumptions reflecting lifestyle and population. For a townwide mean, 50% of the dwellings on a given block are in units of five or more dwelling units: thus, differences in the equation coefficients explain much of the sample variance. For this equation, income factors entered explicitly and served to reduce the value of the constant: the constant plus IL or IM represents the effective constant seen by low and middle income blocks. High income blocks have only the equation constant C. The second model in this sequence, Equation II-2, eliminates inclusion of the income variables: it is very important to note that the relative ordering of the three dwelling unit class coefficients remains the same. In fact, the actual coefficients, almost identical to those in the first equation of the sequence, substantiate the assumption that the explanatory income variables act independently of the dwelling unit variables.

Finally, in the third sequence, age enters as a surrogate for life cycle. As the total number of elderly increase, the total waste output decreases. Similarly, youth tend to add little waste: this can be seen intuitively. Those under 18, especially the youngest, do not consume independently. The marginal waste due to packaging of foods, due to newspapers, etc., diminishes as the household unit size increases. Therefore youth result in an overall increase in waste output, but proportionally less than their numbers would lead us to believe. Here it is important to note that the addition of variables significantly altered the coefficient values of the dwelling unit variables--the independence assumption is not fully justified. Examining cross correlations, one finds elderly highly correlated with larger units (about -.8) and youth highly correlated with buildings with an intermediate number of units. (-.77). Thus, the coefficient estimates are somewhat unreliable and it can be concluded that this expanded model would not suffice as a causal explanation of the underlying processes. The second and third equations in the sequence follow from earlier discussion.

In completing the assessment of the models from a statistics viewpoint, look finally at the traditional goodness of fit measures. These are tabulated below for each equation with the equations run against GALS in Table 8.5 and against GALP in Table 8.6. Recall that GALP is a division of the segment data onto blockfaces on the basis of relative population. Therefore, the statistics cited are the lower and upper bounds, respectively, on the credibility of the models. First, a brief definition of the meaning of these statistics follows. The R-squared, the coefficient of multiple correlation, is technically the ratio of the variance explained to the variance of the sample. The regression fits a line to the sample data: an R-squared of one represents a perfect fit, an R-squared of zero or less means that a fit has not been found. The F-statistic indicates whether the variance between the means of groups of observations is sufficiently large with respect to the variances in the groups. If so, then within specified confidence limits the groups are sufficiently distinct so as to state that they were drawn from different populations (32). Operationally, larger values perform better in F-tests. The standard error of the regression is the estimated standard deviation. The statistic is a special case of the F-statistic used for testing the validity of estimation for each variable independently.

In Table 8.5, note that within each sequence, the statistics from the most to the least desirable models grow progressively worse. In the special case of the upper bounds of Table 8.6, note that they unequivocally dominate the corresponding lower bounds listed in Table 8.5. Of the three sequences, and considering the R-squared measure as most significant, the WASTE II sequence dominates. Although the third sequence appears better at a glance, recall that it did not hold up as a valid prediction due to the colinearity of explanatory groups: inaccurate coefficient estimates should not be used.

A useful device, plotting the residuals (the differences between the actual and the fitted values) against the fitted values, highlights the relationship between the magnitude of the quantity being fitted and the error associated to the fit. Ideally, the errors occur independently of the magnitude: sometimes in practice, increasing error is observed with increasing magnitude

Equation Number	Dependent Variable	R^2	F	Degrees of Freedom	t-Statistic Range	Approximate Standard Errors								
						c	RENTED	OWNED	IC	IM	DU1	DU24	DU50	DUTOT
I-1	GALS	.273	18.8	2	3.44-5.12	243	2.7	12.1						
I-2	GALS	.240	32.0	1	5.66-8.87	182								3
II-1	GALS	.361	10.9	5	1.48-4.15	327			417	330	14	9	3	
II-2	GALS	.364	16.5	3	2.55-5.57	256					14	7	3	
II-3	GALS	.240	32.0	1	5.66-8.87	182								3
III-1	GALS	.382	8.4	7	.79-3.49	327			419	328	18	17	9	
III-3	GALS	.364	16.5	3	2.55-5.57	256					14	7	3	

Table 8.5 Goodness of Fit Measures (GALS)

Equation Number	Dependent Variable	R	F	Degrees of Freedom	t-Statistic Range	Approximate Standard Errors								
						c	RENTED	OWNED	IC	IM	DU1	DU24	DU50	DUTOT
II-1	GALS	.459	16.4	5	.95-5.31	325			316	328	14	9	3	
II-2	GALS	.435	25.4	3	2.74-6.73	255					14	7	3	

Table 8.6 Goodness of Fit Measures (GALP)

of quantity being predicted. This trait, heteroscadasticity, simply means that a larger block output would be likely to show higher error. Correction can be done, but the problem was not serious here. In the sample Brookline problem, the residual plots were slightly heteroscadastic due to the variations in block sizes. The development of census variables to avoid these difficulties presents an interesting area for future research.

Finally, all the equations have a large constant associated to them--the equation then states that given a waste output, waste is produced independent of the levels of the other indicators. Clearly this makes no physical sense and leads to the question of what is missing. The variables chosen for the actual calibration did not display the depth outlined in the hypothesized underlying causality. This too results from the character of available data. One other possibility might lead to errors of this sort--that being the introduction of systematic bias into the data base. In this project, another party did the data design and collection. Perhaps in definition, collection, or processing non-random errors were introduced (e.g. consistently rounding up the collection time). Part of the problem may be specific to the data base and town with which the project worked.

The Brookline prototype exemplifies the type of statistical results that may be anticipated. The easily run models may test several alternatives for districting: then the system manager or other decision maker could choose that which best matches primary and implicit secondary objectives. If model errors are unbiased, then any inconsistencies would tend to be reduced in aggregating over blocks to achieve a final district. In any case, the purpose of this section was to review one application: the improvements that will be seen in the future will stem largely from more data better suited to model the underlying causality proposed for the waste generation model.

8.4 Validation

The next step to produce the output desired for districting is to employ the waste output statistics gathered in a time prediction model: districting follows by equalizing expected collection time assigned. As an intermediate step, one districting plan based solely on the waste output will be discussed.

Validation should be attempted by calibrating the model with a small part of the overall data, using the model for prediction in areas with reserved data, and then comparing the actual to the predicted results. We did not have sufficient data to take this course of action. Instead, the calibrated models were used to predict waste output for the entire town of Brookline and internal checks were made to test for validity. This is not sufficient for an actual application. For the three plans, the observed mean, variance, and standard deviations are shown in Table 8.7. Recall the actual statistics shown in Table 8.2 where the variable GALS is chosen as the lower bound. The mean predicted output is higher, but this output most closely approximates the actual observed waste generation. The variance of the actual sample exceeds that for the predicted sample: this is not surprising since the R-squared measure indicates unexplained variation. The standard deviation for the estimate similarly does not reflect the variance of the sample. The cross correlations, Table 8.7, show that all three sample outputs are highly correlated. This is expected, but at least suggest the models perform correctly.

A second step in assessing this validity was to use the model to generate districting plans. The IOWA REDIST package described in Chapter 5 was used and the output as plotted on a Brookline town map appears in Figure 8.8. Only approximate comparisons are made here: the Sanitas data enabled us to plot the actual routes for comparison. Several of the predicted districts matched almost identically actual routes as traced from field surveys (for examples our routes 28 and 6). As expected, the northern sector contains more collection areas than the less densely populated south--sectors tend to be reasonably compact but with a tendency towards having penninsulas. Forty districts were generated as this is the existing level of service for Brookline. In Section 8.5 districting based on the time prediction will demonstrate the implications of fewer or greater numbers of servers. Revisions of that sort are trivial and inexpensive using a districting methodology.

In the forty district plan, the maximum allowable variance between the smallest and the largest districts was 20%. Districting on the basis of predicted waste output was both efficient and inexpensive, but the equitable workload model would be preferred in many applications.

8.5 Time Models

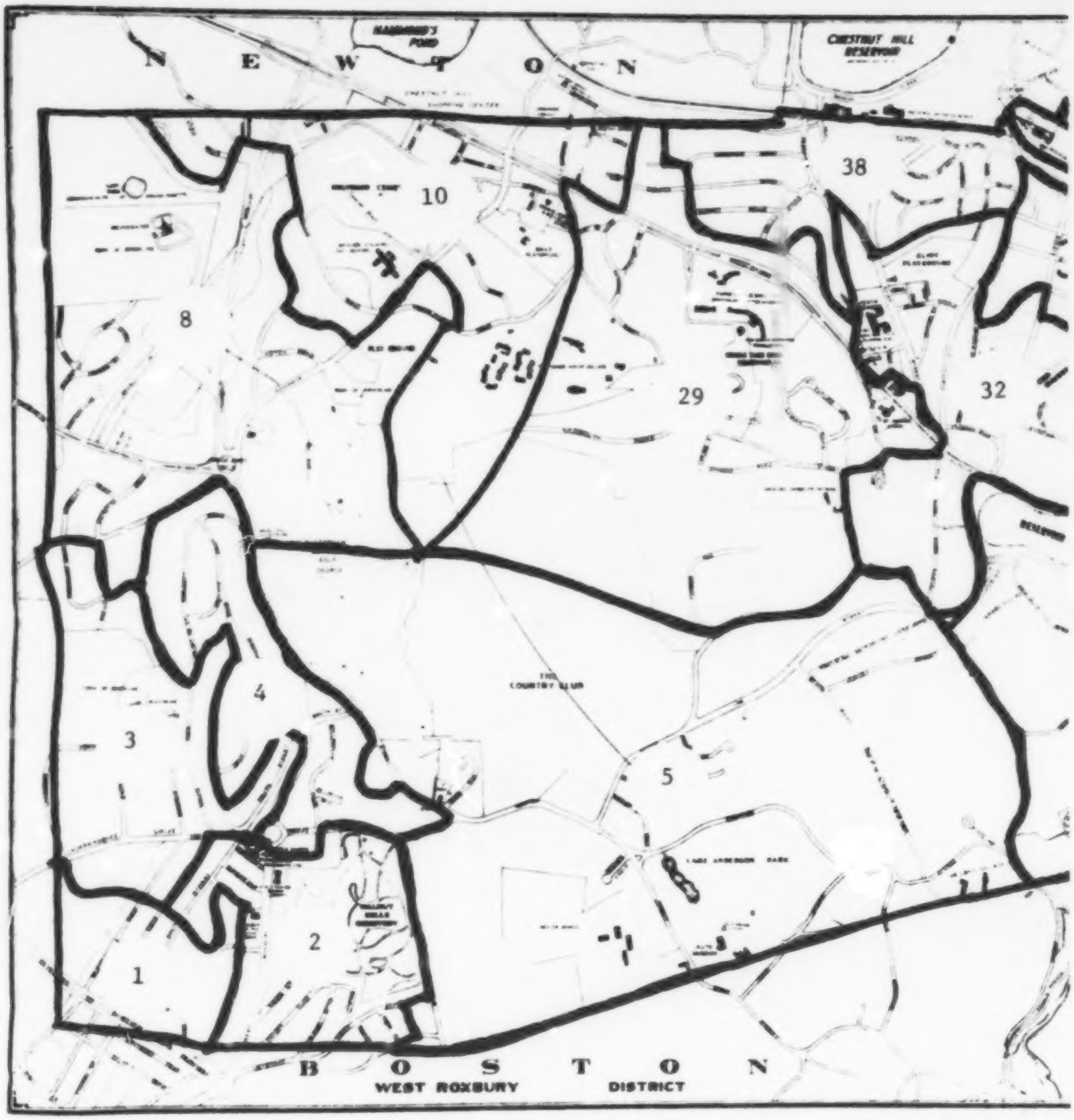
The Sanitas data yielded 165 blockfaces from which the time model could be calibrated. This section first reviews the statistical measures output and then discusses the results of application to actual time prediction and districting runs. An econometric

Variable	Mean	Variance	Standard Deviation
GALS1 (from WASTE I)	2392	$.269\ 10^7$	1639
GALS2 (from WASTE II)	2320	$.144\ 10^7$	1200
GALS3 (from WASTE III)	2364	$.249\ 10^7$	1577

Table 8.7 Predicted Waste Load Statistics

	GALS1	GALS2	GALS3
GALS1	1.0000	0.81341	0.92871
GALS2	0.81341	1.0000	0.91332
GALS3	0.92871	0.91332	1.0000

Table 8.8 Correlation Matrix



NEWTON
HAMMOND'S POND
CHESTNUT HILL RESERVOIR
38
10
8
29
32
4
3
5
THE COUNTRY CLUB
LARZ ANDERSON PARK
2
1
BOSTON
WEST ROXBURY DISTRICT

Fig. 8.8: Forty Districts Based on Predicted Waste

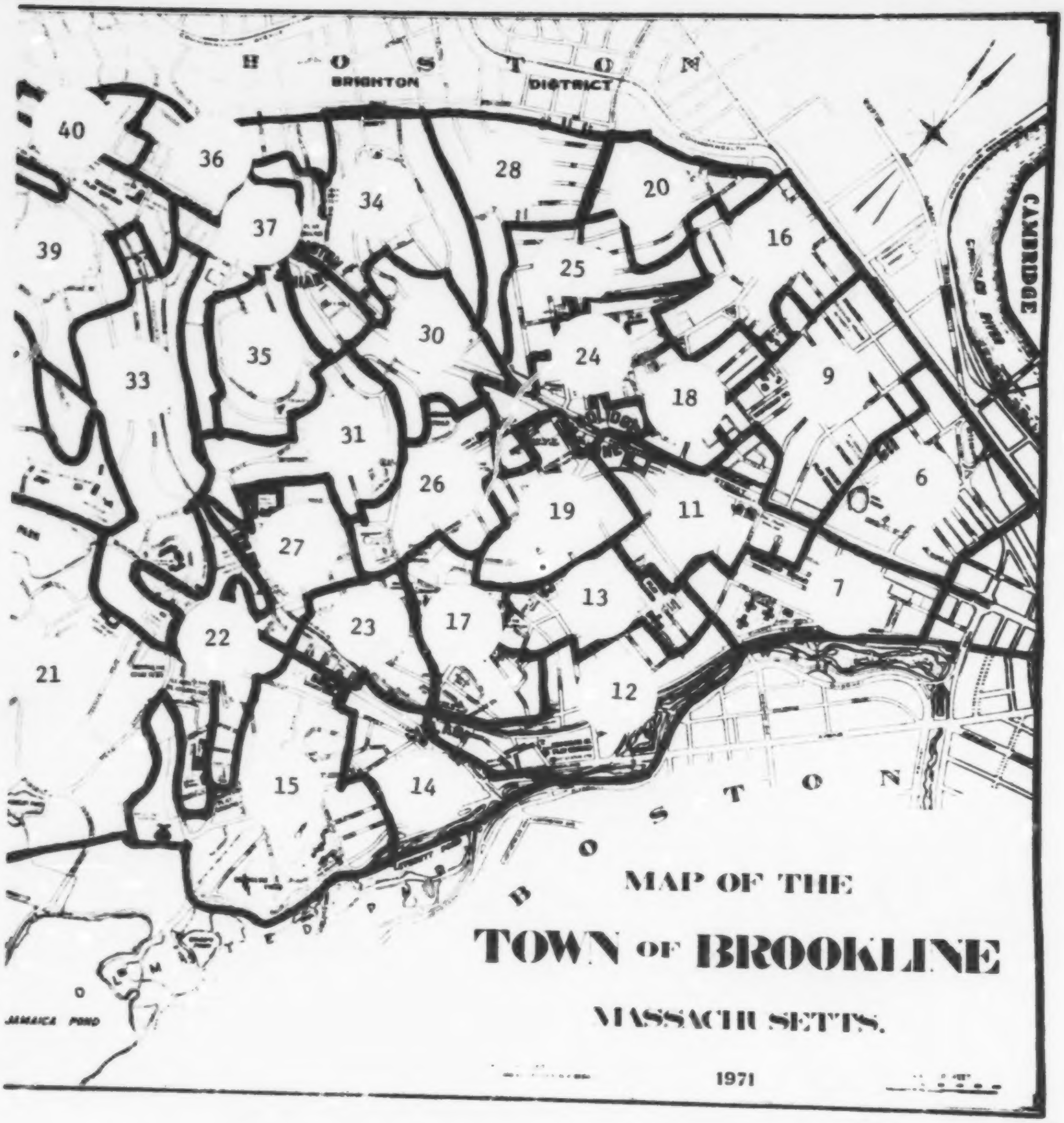

B O S T O N
BRIGHTON DISTRICT
CAMBRIDGE
40
36
37
34
28
20
25
16
39
30
24
9
35
33
18
31
26
6
19
11
27
13
7
17
23
22
21
12
15
14
B O S T O N
JAMAICA POND
MAP OF THE
TOWN OF BROOKLINE
MASSACHUSETTS.
1971

Figure 8.8 (Contin.): Forty Districts Based on Predicted Waste package was again used to perform the standard linear regression runs. The time model output is shown in Table 8.9. DIST is the distance around the block perimeter in hundreds of feet, GALS the measured uncompacted gallons waste output; TIME the predicted collection time in minutes. The R-squared, F, and t statistics are all acceptable. The large constant may be explained as earlier, probably due to the missing causality unrepresented in the final version of the model. In this instance, the residual plots exhibited little heteroscadastic behavior, probably due to less collection time variation on block segments. Intuitively, the independence of distance and waste output is acceptable over certain ranges.

This calibrated model was then used to predict collection times for the census blocks and these in turn aggregated into collection districts. Consider first the forty district plan shown in Fig. 8.9. The predicted waste generated by WASTE II and the time model (run from identical starting points) is shown in the waste-based Figure 8.9. Note that the larger districts (e.g. in 8.8) tend to become smaller (e.g. in 8.9) as the larger distances travelled require longer collection times .

The time model actually used as a basis for districting was modified from the prediction model. As an approximation because the waste load data is by blocks and not by street segments, the time to collect a block was considered on average as only a fraction of the total time required for block collection. The assumption was made that on many streets both sides of the block could be collected simultaneously, therefore it double counts to consider all blocks at their full collection time value. As an arbitrary correction, one-half the perimeter was chosen for DIST instead of the full perimeter. This fraction represents the assumption that all segments could have both sides collected simultaneously; it is a lower bound on the anticipated time for total citywide collection. In practice, the fraction should be chosen after consultation with a decision maker responsible for assigning blocks to single or both sided collection.

Another extension was the addition of the expected haul time into the districting problem. A priori, the routes are undefined before districting and the probability that a haul will occur from a given block k, p_k, is simply its fraction of the total district load. That is,

$$p_k = \frac{\text{wasteload in block } k}{\text{total desired district load}} \qquad (8.1)$$

Desired district load is chosen because a priori the district load

Dependent Variable	Independent Variable	Estimated Coefficient	t-Statistic
TIME	GALS	0.414211E-02	7.31455
	DIST	0.576630	4.59936
	C	2.29268	3.21629

Statistical Measures

R-SQUARED = 0.4594
F-STATISTIC (2,182) = 77.3207
Standard Error of the Regression = 5.64157

Table 8.9 Ordinary Least Squares Time Model

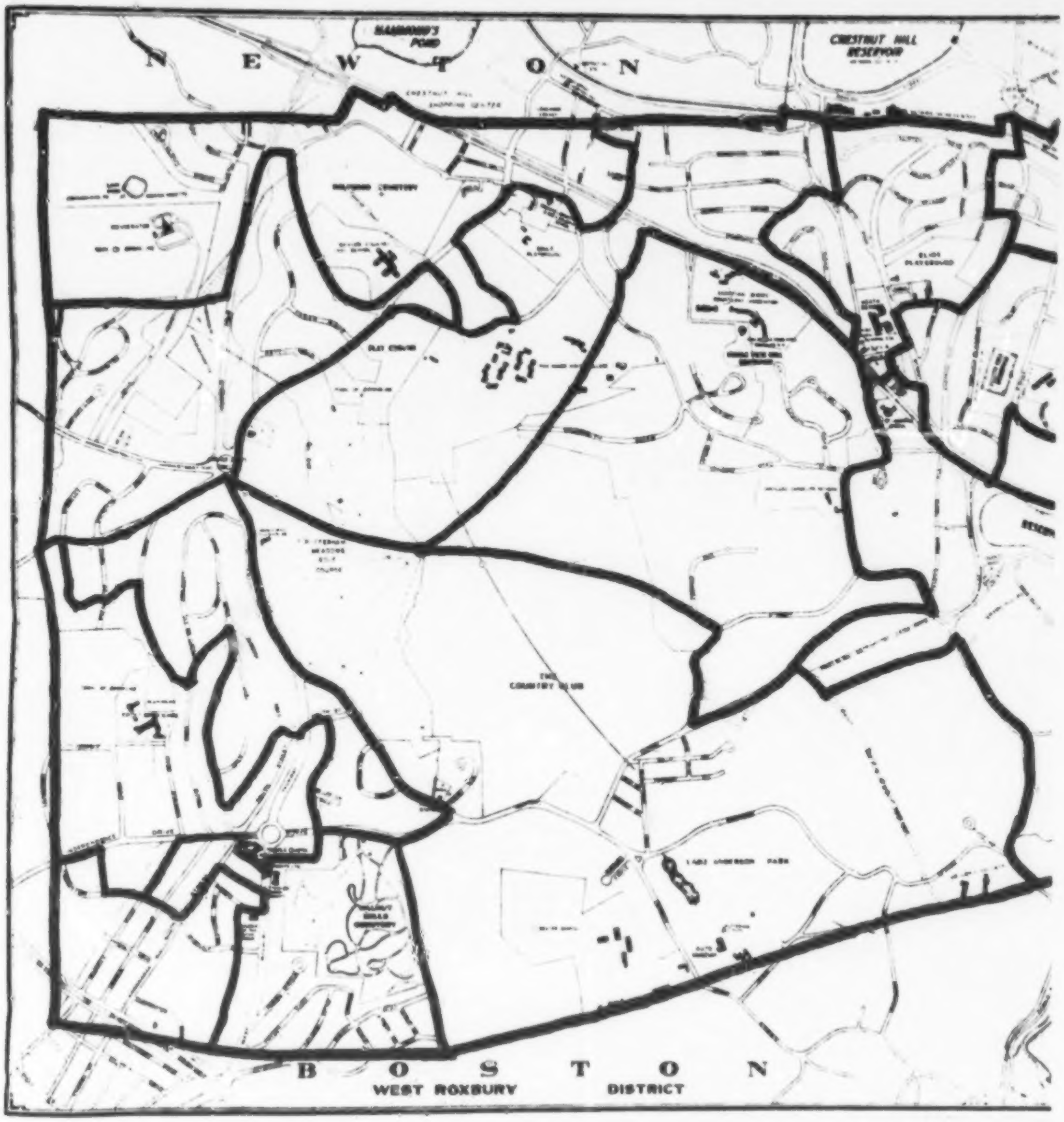

HAMMOND'S POND
N E W T O N
CHESTNUT HILL RESERVOIR
THE COUNTRY CLUB
B O S T O N
WEST ROXBURY
DISTRICT

Fig. 8.9: Forty Districts Based on Predicted Collection Time Including Haul

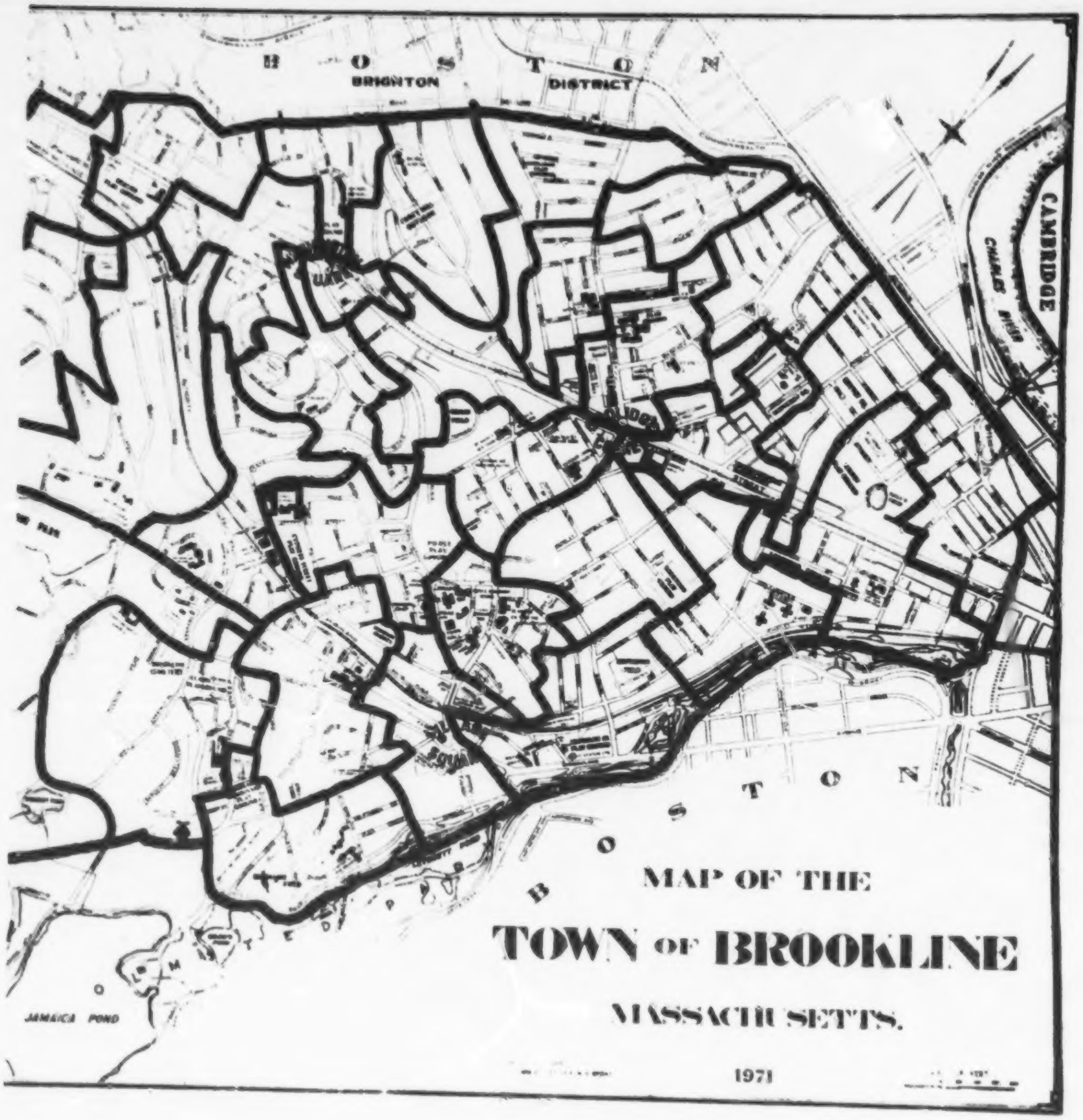

B O S T O N
BRIGHTON
DISTRICT
CAMBRIDGE
CHARLES RIVER
B O S T O N
MAP OF THE
TOWN OF BROOKLINE
MASSACHUSETTS.
1971
JAMAICA POND

Fig. 8.9: (Contin.) Forty Districts Based on Predicted Collection Time Including Haul

cannot be known. Therefore, the expected haul time for district n, T_n, is simply:

$$T_n = \sum_{k=1}^{r} p_k t_k \qquad (8.2)$$

where the set r represents the blocks proposed to comprise the district and t_k the time haul would require from block k to the disposal point. Each time a block enters a district, the time componant due to haul must be calculated and included as a basis for retention. The haul expectation must be multiplied by the total anticipated number of hauls per district per day. Similar analysis might be made for travel to and from garaging or maintenance facilities. Distances from block centroids to garage or dump are readily measured, but the actual haul times must be calculated using an assumed travel speed.

Districts including these extensions and based on one truck fewee or more per day, respectively, are shown in Figures 8.10 and 8.11. The ratios of the largest to smallest district collection loads are shown in Table 8.9. The greater the number of districts, in general, the larger the ratio one would expect given a fixed number of starting cells. This holds for the two smaller cases, but does not for the largest number of districts chosen. The differences in the ratios can probably be ignored. The exercise demonstrates that once predictions have been made, the decision maker has great flexibility in testing proposed system changes. The effects if additional or fewer trucks on workloads and the types of assignments to be made are easily assessed. Here graphical output facilitates opinion gathering--from collectors, politicians, the public. Once a reasonable design level (or set of levels) has been chosen, districting for this level can be done accordingly. The time models, like the waste generation models, should be validated with reserved data. Although costly at first, an appropriate model form will probably remain applicable within a given community. This would have been the most desirable validation approach, but, if infeasible, then the best test would be feedback from those actually involved in running the system.

8.6 Extensions

The sophistication necessary to produce and interpret results can be seen through the prototype analysis. By calibrating, validating, and then districting with a basis of readily available

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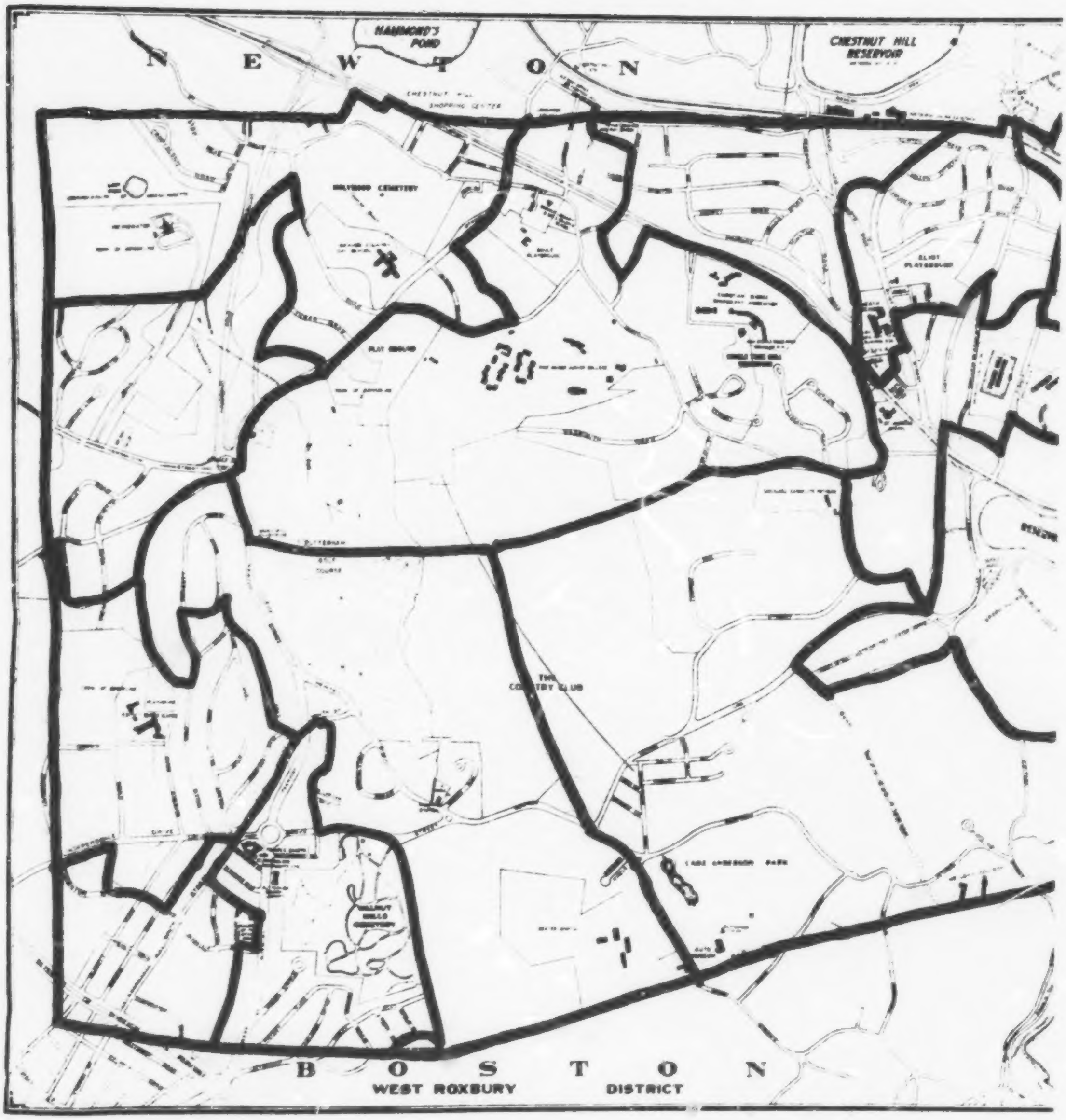
HAMMOND'S POND
N E W T O N
CHESTNUT HILL RESERVOIR
CHESTNUT HILL SHOPPING CENTER
HOLYWOOD CEMETERY
PLAY GROUND
ELIOT PLAYGROUND
PUTTERHAM GOLF COURSE
THE COUNTRY CLUB
LARZ ANDERSON PARK
WALNUT HILLS CEMETERY
B O S T O N
WEST ROXBURY DISTRICT

Fig. 8.10: Thirty-Five Districts Based on Predicted Collection Time Including Haul

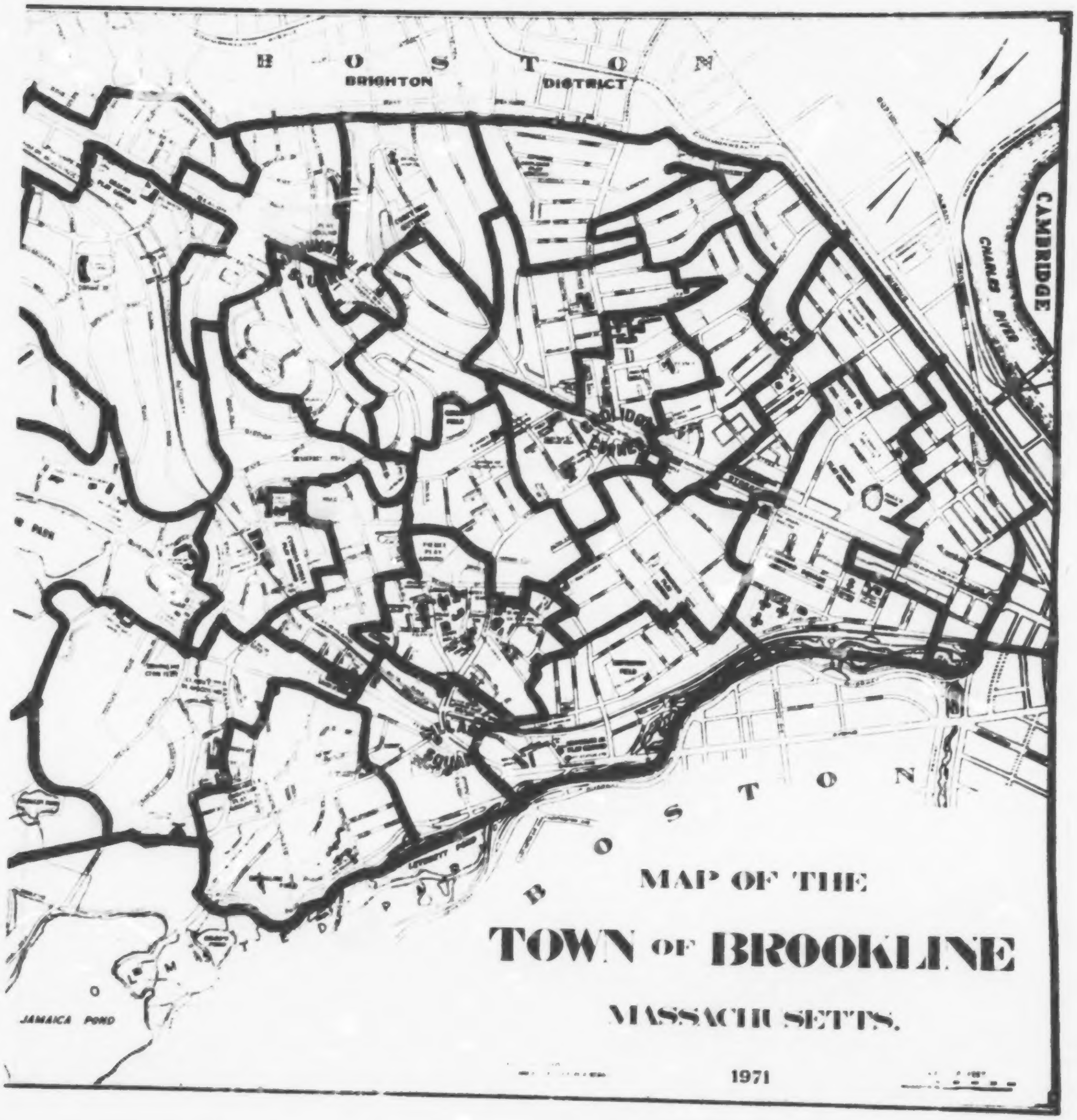
BOSTON
BRIGHTON
DISTRICT
CAMBRIDGE
CHARLES RIVER
COOLIDGE CORNER
VILLAGE SQUARE
BOSTON
JAMAICA POND
MAP OF THE
TOWN OF BROOKLINE
MASSACHUSETTS.
1971

Figure 8.10 (Continued): Thirty-Five Districts Based on Predicted Collection Time Including Haul

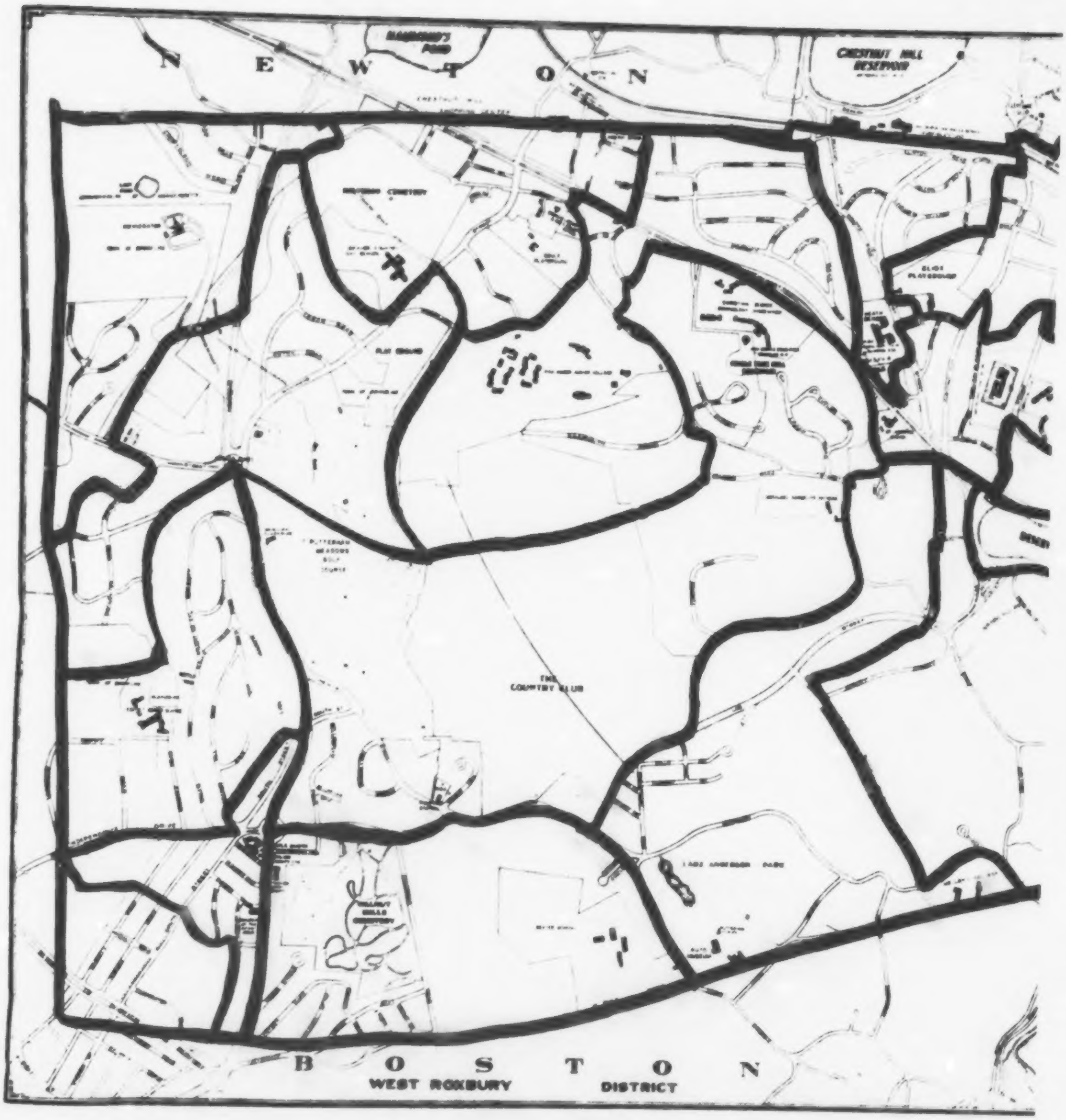
HAMMOND'S POND
N E W T O N
CHESTNUT HILL RESERVOIR
ELIOT PLAYGROUND
THE COUNTRY CLUB
LARZ ANDERSON PARK
B O S T O N
WEST ROXBURY
DISTRICT

Figure 8.11: Forty-five Districts on Predicted Collection Time Including Haul

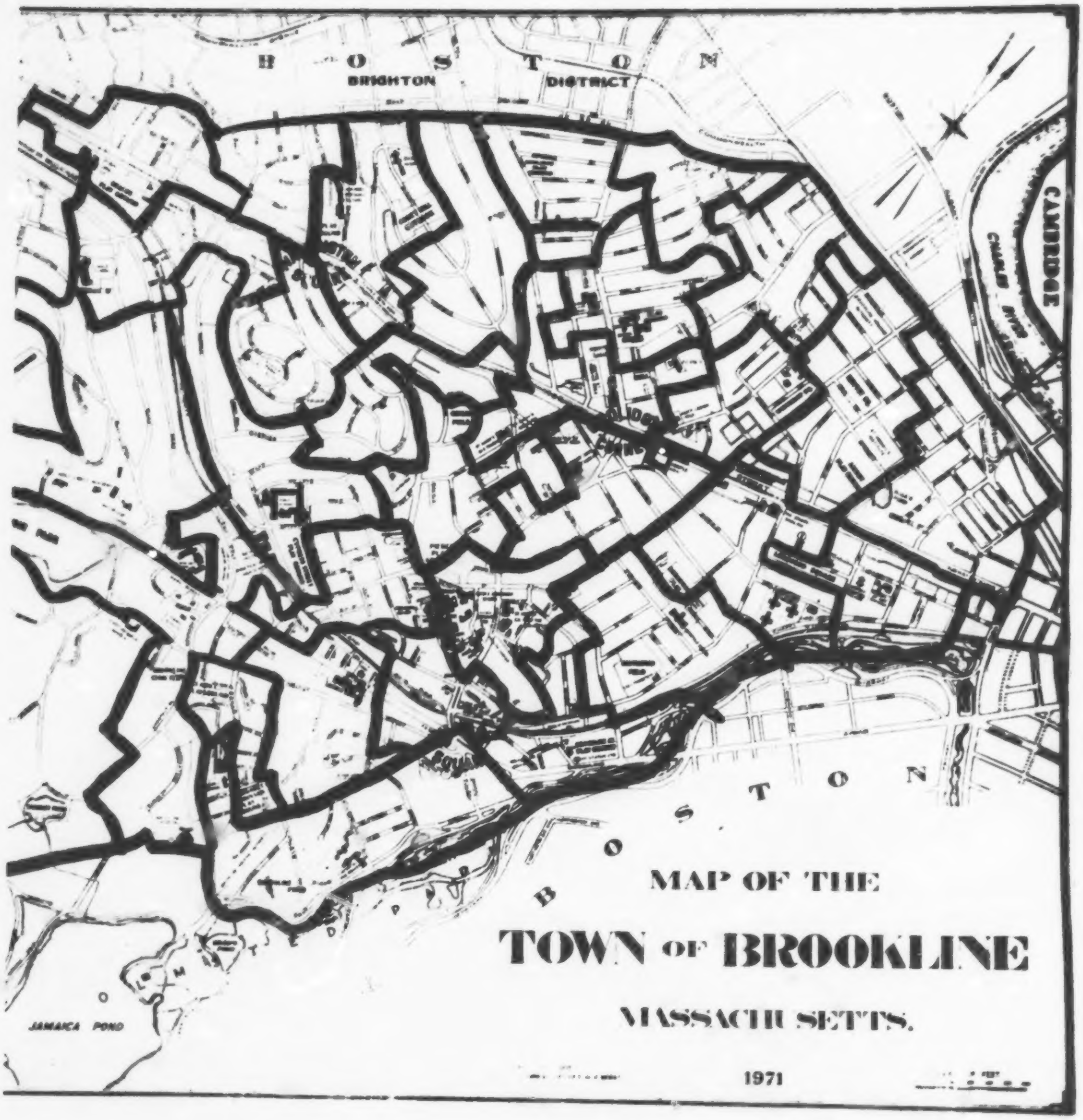
B O S T O N
BRIGHTON DISTRICT
CAMBRIDGE
CHARLES RIVER
B O S T O N
MAP OF THE
TOWN OF BROOKLINE
MASSACHUSETTS.
1971
JAMAICA POND

Figure 8.11: Forty-five Districts on Predicted Collection
(Continued) Time Including Haul

data, it is hoped that the methodology demonstrated is accessable to any moderate sized community. The proposed scheme need not be used to totally redesign a system--auxiliary constraints may be too great. For example, the town may have a fixed number of crews. Here the results may be applied to develop equitable collection routes using one of the LP based districting schemes and perhaps even choosing the existing district centers for a first pass. Alternatively, major changes in operations may be readily examined once satisfactory predictions for block waste output are obtained. For example, a variety of equipment or crew sizes resulting in vastly different productivities might be examined for implementation. The advantages of a simple model are in examining a large number of alternatives.

The cost of the analysis proposed and the time required are not very great. The Brookline example required roughly 4 people months which included extensive research in model design: less time would be required for a similar case now. Data collection would require additional effort and expense--but the data collected with a specific purpose in mind would be easily processed and utilized. The computer packages are generally available: some of the documentation is found in Volume 2 of this report (49).

Development of more extensive prototypes and establishment of a field trial would be a valuable area for future research undertaken in this project. Brookline only exemplified the ease of prediction and districting--the heuristic routing is readily applicable from the results once more validation had been undertaken.

ANALYTICAL MODELS FOR PLANNING REGIONAL SYSTEMS

Managers of solid waste systems have viewed the concept of "regionalization" with favor for several years. Economies of scale seem to be present in solid waste treatment or landfill which suggest the construction of large centralized plants to minimize costs. It appears easier in the abstract to find one site for a large facility than to find several for smaller operations.

Very few regional systems have been implemented, however. No community wishes to receive waste from its neighbors, and no rural area wants the "garbage" of metropolitan areas. Negotiations break down when considering the prime question of "Who gets the dump?" One characteristic situation has the larger cities, without landfill space and with the most waste, attempting to convince the more rural areas to take their waste (usually without much success). Some states have entered into the discussions, and some regional governments have taken the responsibility. (110, 52, 91)
Still, the situation in most areas is fairly grim. with all the professionals agreeing that regionalization is *the* answer, and the governments feeling it is impossible and hoping for a miracle.

Mathematical models will not provide the miracle. They can be used, though , to give the problem more substance. One of the axioms of systems analysis is that better decisions are made if the decision-makers have better information. At times this assumption is difficult, but it appears to give the most hope for equity, economy, and the other desirable goals in political decisions.

It is, therefore, important to look at the sorts of questions which the representatives of the various involved communities (for example), might wish to ask in an attempt to develop a regional waste handling system. A reasonable planning horizon for such a system should be identified, probably something like 30 years. Some description should be given of what appears to be the least cost system, and of how sensitive it is to demand projections and waste processing technology. These are basic engineering data; the sort of information which would be expected if a contract was given to plan the least expensive system.

Designing the least-cost system, though, really begs the question. The issue of importance is the trade-off between cost and equity. Nothing could be fairer than for each generator of solid waste to dispose of it himself in a sanitary manner on the premises, without impacting anyone else. The cost, though, would be prohibitive. At the other end of the scale, the cheapest system often involves one giant incinerator or landfill with the nearby residents receiving *all* the adverse impacts from the whole region's waste. In many past cases, even minimal levels of sanitation have not been required, which greatly increases these impacts. There is an obvious trade-off here, and a rational designer would look for a system which is acceptable from both cost and equity standpoints. The collective group of decision-makers assumed above are also likely to be searching for such a design: it should be efficient, to keep costs low; it should be equitable, so that no single area receives an unreasonable share of the environmental impacts (whether traffic, odor, or cost); and it should be Pareto optimal, so that there is no change which could be made which would improve the design in favor of one community without hurting another.

The question arises of how such a system should be designed. A great deal of work has been done on designing least-cost systems, as will be described below. These have limited value in looking at the real issues, though. Formalized negotiation techniques have also been used, with some success. Games have been developed where the decision-makers can learn about the system and test various alternative configurations against cost. Attempts have been made without any support from analysts, through the standard political channels. Deceit has also been used, where a community attempts to develop its disposal point in secret so as not to arouse a reaction from local residents.

It is fairly easy at this point to describe the sorts of aids which analysts should provide. Whether they can is another question entirely. Any model or technique should look at the real questions of cost and impacts, both at the neighborhood and regional levels. It should be possible to screen the alternatives, to reduce the space of possible choices to those which are technically efficient and potentially equitable. The case study of the Boston area described below includes sixteen generating areas, fifteen possible facilities, and three time periods. The number of potentially feasible systems is enormous, since the design must consider waste shipment as well as facility construction and expansion.

The model developed in the course of this project is such a "screening" model. It is designed to look at aggregate costs and equity variables for regional systems, and to choose that system which is best for some set of initial design goals. It can be used to investigate questions of facility location, time staging, the effect of demand changes, and most important, the cost of building and operating systems which show different amounts of "equity". It becomes very easy to generate such things as transformation curves, which show the cost equity trade-off explicitly on a graph. Since the system chosen is described in detail (cost, capacities, and amounts handled of all processing or disposal facilities, and shipment quantities from each generating area to each facility), the political issues can be discussed with direct reference to the costs of reaching an acceptable design. Once this is done, use of simulation models or full engineering design may be desirable in an attempt to look in more closely at what appear to be the most acceptable systems.

9.1 Planning for Economic Efficiency: Mathematical Programming Models

The "facility location" problem is a classic area for operations research. The desire is to choose the best location and timing of one or a set of facilities to meet some demand which is given exogenously. The problem does not apply in some areas where demand is strongly dependent on supply (e.g. highways), but may be usable in solid waste. The problem of locating facilities in order to minimize facility setup and transportation cost has been treated by numerous economists and planners since Weber wrote his classic On the Location of Industries. (137) The problem is a more difficult analogue to the transportation problem, which seeks to minimize shipping cost while filling a set of demands D_j by a set of supplies S_i. Costs for shipping a unit from i to j reflect the spatial and temporal dispersion of the elements in the network. The transportation problem is written as

$$\text{MIN} \quad \sum_{i=1}^{m} \sum_{j=1}^{n} C_{ij} \cdot X_{ij}$$

$$\text{S.T.} \quad \sum_{j=1}^{n} X_{ij} \leq S_i \qquad \forall\, i$$

$$\sum_{i=1}^{m} X_{ij} \geq D_j \qquad \forall\, j$$

$$X_{ij} \geq 0$$

where

X_{ij} = Units shipped from i to j

C_{ij} = Cost of shipment of one unit from i to j

S_i = Supply at source i

D_j = Demand at site j

m = Number of feasible facility sites

n = Number of demand

The facility location problem is of more current interest than the easily solved transportation problem. The facility location problem is of the form

$$\text{MIN} \quad \sum_{j=1}^{n} \sum_{i=1}^{m} C_{ij} \cdot X_{ij} + \sum_{i=1}^{m} F_i \, (Y_i)$$

$$\text{S.T.} \quad \sum_{j=1}^{n} X_{ij} - Y_i \leq 0 \qquad \forall\, i$$

$$\sum_{i=1}^{m} X_{ij} \geq D_j \qquad \forall\, j$$

$$X_{ij} \geq 0 \qquad \forall\, i,j$$

$$Y_i \geq 0 \qquad \forall\, i$$

where X_{ij} = Units shipped from i to j

Y_i = Units of capacity at source i

D_j = Demand at area j

C_{ij} = Cost to ship one unit from i to j

$F_i(Y_i)$ = Cost to construct a facility at site i with Y_i units of capacity

m = Number of feasible facility sites

n = Number of demand areas

The facility cost function, $F_i(Y_i)$ is frequently a function displaying a high initial charge independent of capacity (representing the cost of land, utilities installations, planning and design cost, legal expenses, etc.) plus certain costs which increase as capacity increases. The concave nature of the facility cost function (reflecting decreasing average costs, or increasing returns to scale) has presented a problem to analysts and a number of efforts have been made to treat this aspect of the facility location problem. If the facility cost element were linear or convex, the optimal solution of the problem would be a fairly straightforward transportation problem.

Baumol and Wolfe (12) treat the facility location problem as a transportation problem, and then proceed to alter their solution using heuristic techniques (a heuristic is a set of rules which will lead to good, near optimal solutions. No proof of optimality or solution quality can be made for a heuristic).

Kuehn and Hamburger (68) utilize a concave cost function of the form

$$F_i(Y_i) = a_i + b_i Y_i \quad \text{if the } i^{th} \text{ facility exists}$$

$$= 0 \quad \text{otherwise}$$

This representation is appealing since the fixed facility charges can be combined into the a_i term, while b_i represents the marginal cost (assumed constant here) for adding a unit of additional capacity. Kuehn and Homburger employ a heuristic solution strategy which increases the number of plants in operation until there is no further reduction in system cost. Linear transport costs are assumed.

Feldman, Lehrer and Ray (38) also assume linear transportation costs, and a continuous concave facility cost function is utilized. Their heuristic strategy of cost reduction eliminates less desirable facilities one at a time, after starting with all plants in existence.

Balinski (10) formulates the problem with linear transport costs and a constant facility cost which is independent of plant capacity. Although his approach becomes impractical as the problem size increases, Balinski's integer programming approach can find optimal solutions for small problems. His approach uses Gomory's integer programming cutting plane method (48) along with a partitioning procedure developed by Benders (16). The partitioning procedure is used in an effort to extend the solution method to larger problems. This approach has not been attempted for large problems due to computer time requirements.

Effroymson and Ray (36) also use linear transport costs and a constant facility cost. However, they formulate the problem so that there are fewer constraints than in Balinski's approach. In addition, a branch and bound solution procedure is used. The branch and bound strategy searches various facility construction alternatives, and abandons the analysis of a particular site choice if another previously studied site is dominant. Effroymson and Ray have tested this procedure and have obtained good computational results. One drawback of this technique is the form of the facility cost function.

Spielburg (116) has taken much the same approach as Effroymson and Ray, but has added several refinements which speed up computation time.

Murty (96) has proposed another optimization technique for the fixed charge problem referred to as "extreme point ranking." Murty uses the fact that the optimal solution to problems with concave objective functions will lie on the boundary of the convex feasible region formed by linear constraints in his algorithm. The procedure ranks vertices of the convex set in order of increasing transportation costs. The fixed facility charges corresponding to the least transport cost strategy are then considered, and an initial upper bound of total cost is established. Murty's scheme moves from the lowest transportation cost strategy to other strategies in order of increasing transport cost, and adds the proper fixed facility costs to each strategy to determine the least total cost solution. The technique reduces the old upper bound of total cost whenever it exceeds the total cost for a newly considered strategy. The procedure terminates when the transport cost exceeds the current total cost upper bound minus the sum of the minimum feasible fixed facility charge.

Cabot and Francis (21) extended Murty's work to include facilities with continuous concave cost functions.

Marks (84) devised an approach to treat transshipment through capacity constrained facilities with concave facility costs. He used linear approximations for linear concave facility charges and solved initially using an out-of-kilter algorithm. Next a branching procedure takes place which accounts for previous facility costs approximations, and leads to an optimal, least total cost strategy. Marks used as his example problem the location of transfer sites for the handling of solid waste in Baltimore.

Skelly (115)treated the problem of location of facilities and allocation of service areas using a simplex based algorithm developed by Walker (134). Skelly further expanded the problem to include transshipment as well as analysis of a multiple time period. Skelly was not able to analyze time staging of new facility construction, despite the multi-time framework of his analysis. The Walker heuristic solved for a local optimum, and then attempted to displace the basis sufficiently to seek out a global optimum. Skelly performed his analysis using a regional solid waste disposal district as a test case.

The problem of time staging the construction of projects under various conditions is also pertinent to the work done here. One of the first works to treat this problem was editied by Manne (81). Manne presents a mathematical scheme for determining the optimal stage length between new capacity expansion, given an arithmetic growth in demand. This result utilizes only the economies of scale of the technology in question and the opportunity cost of capital. Further elaboration is performed in the book using industrial development in India as an example.

Scott (114) treats the problem of the staggered construction of public facilities (because of budgetary or other constraints) in order to maximize public utility. In Scott's work, demand is stationary, over time and he is principally concerned with ordering the introduction of facilities. No effort is made to discount costs to net present value.

Howard (59) considers a number of types of demand growth and time horizons, proposes several algorithms, and proves they lead to optimal solutions.

Besides these authors, the solid waste facility location problems has also been modelled by Hekemian (52) and Kühner (69), who have developed further extensions in terms of economic efficiency models. Consultants are also beginning to enter the field and apply such models in the design of regional systems for their clients (126, 110).

9.2 Other Analytic Methods

Hekemian (52,53) used formalized negotiation methods in developing the design of the Kansas City Metroplan Regional Solid Waste Management System. Questionaire techniques similar to the Delphi method were used to assess the preferences of the decision-makers, and a system was developed which maximized these objectives. One crucial step was to keep each of the decision-makers informed about progress. Preference assessment may be an important tool in such situations, as has been suggested in other research (58,37). The successful adoption of the plan speaks highly for the effectiveness of the technique, at least in this single application.

Klee (66) and Wahi(133) have each developed games intended to teach decision-makers about the available options and the performance of solid waste systems. These are basically facility location and routing games, and involve on-line operation with a computer performing the necessary bookkeeping. While valuable for "consciousness-raising" among the political body, they do not provide an explicit view of the trade-offs involved, nor do they insure efficient design. One problem with such games is that the situations are often highly abstracted, so that many of the real interactions may be missing, or reduced in importance. The games may show the potential value of regionalization, but they are really not a major aid in designing the regional system.

Some recent work by Adrian, et al (1) suggests another approach. The problem there was one of regionalization of waste water treatment, but the issues are similar. Their goal was to look for a set of charges for service which communities would pay which would solve the Pareto optimality condition -- basically using transfer payments to counteract the concentration of the environmental impacts. Costs must be met, and an equitable distribution is desired. The technique may be of value in some situations, but it again does not help in choosing efficient designs: it only gives a method for making a design more acceptable. The assumptions are also fairly restrictive, so that the whole political process cannot be subsumed into their methodology.

9.3 Development of a Dynamic Solid Waste Haul and Facility Location Model

The form of the model derived in this report is as follows:

$$\text{MIN} \quad \sum_{i=1}^{m} \sum_{t=1}^{p} \lambda_t \cdot \gamma_{it}(P_{it}) + \sum_{t=1}^{p} \sum_{j=1}^{n} \sum_{i=1}^{m} \lambda_t C_{ijt} \cdot X_{ijt} \tag{1}$$

$$+ \sum_{t=1}^{p} \sum_{i=1}^{m} \lambda_t \cdot F_{it} \cdot (y_{it}) + \sum_{t=1}^{p} \sum_{h=1}^{m-a} \sum_{g=1}^{a} \lambda_t \cdot C^*_{ght} \cdot T_{ght}$$

Subject to

$$\sum_{i=1}^{n} X_{ijt} \geq D_{jt} \qquad \forall\ j,t \tag{2}$$

$$\sum_{j=1}^{n} X_{ijt} - P_{it} \leq 0 \qquad \forall\ i,t \tag{3}$$

$$P_{gt} - \sum_{t=1}^{t} y_{gt} - Q_{go} \leq 0 \qquad \forall\ g,t \tag{4a}$$

$$\sum_{t=1}^{t} P_{ht} - \sum_{t=1}^{t} y_{ht} - Q^*_{ho} \leq 0 \qquad \forall\ h,t \tag{4b}$$

$$\alpha_g P_{gt} - \sum_{h=1}^{m-a} T_{ght} \leq 0 \qquad \forall\ g,t \tag{5}$$

$$\sum_{t=1}^{p}\sum_{j=1}^{n}\sum_{i=1}^{m} D_{ij}\, X_{ijt} + \sum_{t=1}^{p}\sum_{h=1}^{m-a}\sum_{g=1}^{a} D_{gh} \cdot T_{ght} \le A \qquad (6)$$

$$\sum_{t=1}^{p}\sum_{j=1}^{n}\sum_{i=1}^{m} E_{ij} \cdot X_{ijt} \le B \qquad (7)$$

$$\sum_{t=1}^{p} y_{it} \le S_i \qquad (8)$$

$$X_{ijt} \ge 0 \qquad \forall\ i,j,t$$

$$T_{ght} \ge 0 \qquad \forall\ g,h,t$$

$$y_{it} \ge 0 \qquad \forall\ i,t$$

$$P_{it} \ge 0 \qquad \forall\ i,t$$

where X_{ijt} = units of waste shipped from j to i in period t

y_{it} = capacity added to facility i at the beginning of period t

S_i = total expansion capacity of site i

P_{it} = units of waste processed at site i in period t

T_{ght} = units of waste shipped from treatment site g to final disposal site h in period t

m = number of feasible facility sites

n = number of demand areas

p = number of time periods included in analysis

a = number of intermediate processing centers g

$m-a$ = number of final disposal sites h

The first constraint (2) states that any feasible strategy for solid waste disposal must handle all waste generated at each demand area for all time periods. The D_{jt} terms are the dynamically changing loads which must be treated. These demands are estimates, made with a eye on future area population growth and change in per capita solid waste generation.

Equation (3) states that all solid waste shipped to a disposal facility must be processed or treated.

The third constraint is actually in the form of two separate inequalities. Equation (4a) applies to the processing capacity of all intermediate facilities. The constraint states that the amount of waste processed at site i during period t cannot exceed the initial per period processing capacity of the facility plus all capacity expansions (in units of waste which can be treated in one period). Equation (4b) pertains to the capacity of final disposal sites, or landfills. This constraint states that the sum of waste processed at site through period t cannot exceed initial site capacity plus the sum of all capacity expansions at site h undertaken at the beginning of each period up to and including period t. Equation (4a) depicts a constraint on processing rate, which is appropriate for incineration, transfer stations, and other intermediate facilities. Equation (4b) represents a constraint on cumulative processing, which is appropriate for landfills, since the cumulative volume of waste disposed is the proper constraining factor in landfills.

Equation(5)is a constraint pertaining to transshipment operations at intermediate facilities. The term $\alpha_g P_{gt}$ represents the residue of the intermediate facility g operations, since α_g is the weight reduction factor for facility g. The constraint states that all the processing residue generated at site g must be transshipped to some final disposal site h for each period of operation.

Equations (6) and (7) are public policy constraints which influence system design. Equation (6) limits ton-miles of waste shipments in system operation, and equation (7) limits the number of tons of waste shipped across district lines. The significance of these constraints will be discussed in the next section.

Equation (8) limits facility capacity expansion at a given site. This constraint may be used to reflect site area limitations.

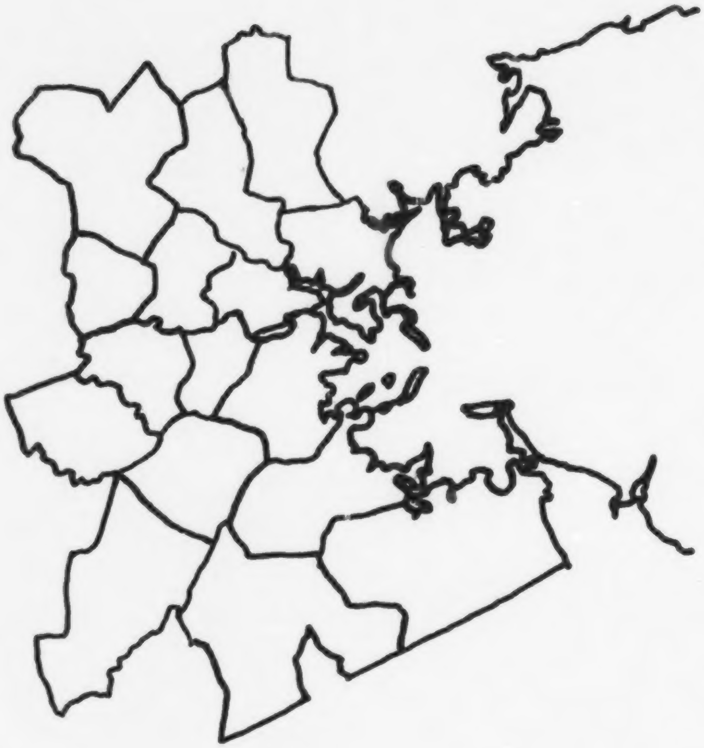

Figure 9.1: Map of Study Region Showing District Boundaries

9.4 Sample Case Study

In order to examine the operating characteristics of the mathematical model, a case study was formulated. The case study centered on the demand for solid waste disposal service in thirty-nine cities and towns in the Boston Metropolitan area for the period from 1970 to 2000. The cities and towns are a mixture of very densely populated core cities and relatively sparsely populated suburban towns which presently comprise the Metropolitan Sewer District. The District is a cooperative intergovernmental alliance which treats and disposes of waste water. The towns have a combined population over 2 million.

In order to carry out the analysis of the mathematical model more efficiently, three ten year time periods were formed to cover the study period. In addition, the 39 cities and towns were aggregated into sixteen districts. A map illustrating the districts can be seen below (Figure 9.1). The aggregation reduces the required number of constraints and variables to be read into the computer, and therby reduces the time required to run the program. Care was taken to aggregate towns into compact districts, with additional effort at combining similar towns into the same districts.

Feasible sites for new solid waste treatment or disposal facilities were chosen on sites of existing or recently proposed solid waste facilities. Reflecting the scarcity of land in the study area, eight of the fifteen facilities are incinerators, one is a transfer station, and six are landfill sites. The landfills are located in the suburban, less populous parts of the area, and the treatment facilities are located in both suburban and dense urban areas. A map showing location of the feasible sites follows (Figure 9.2).

Residential waste loads by district and by period can be seen in Table 9.1. These figures were obtained from a recent statewide solid waste management study (110). The waste load projections were made using population projections and the results of a residential solid waste generation inventory recently undertaken by the Massachusetts Department of Public Works. Although rate in percapita waste generation appears to be low in several instances, these projections were considered to be generally reasonable, and the best available data.

The model sample problem formulation is purposely structured with limited connectivity between generating areas and disposal or treatment facilities. This means that it is not possible

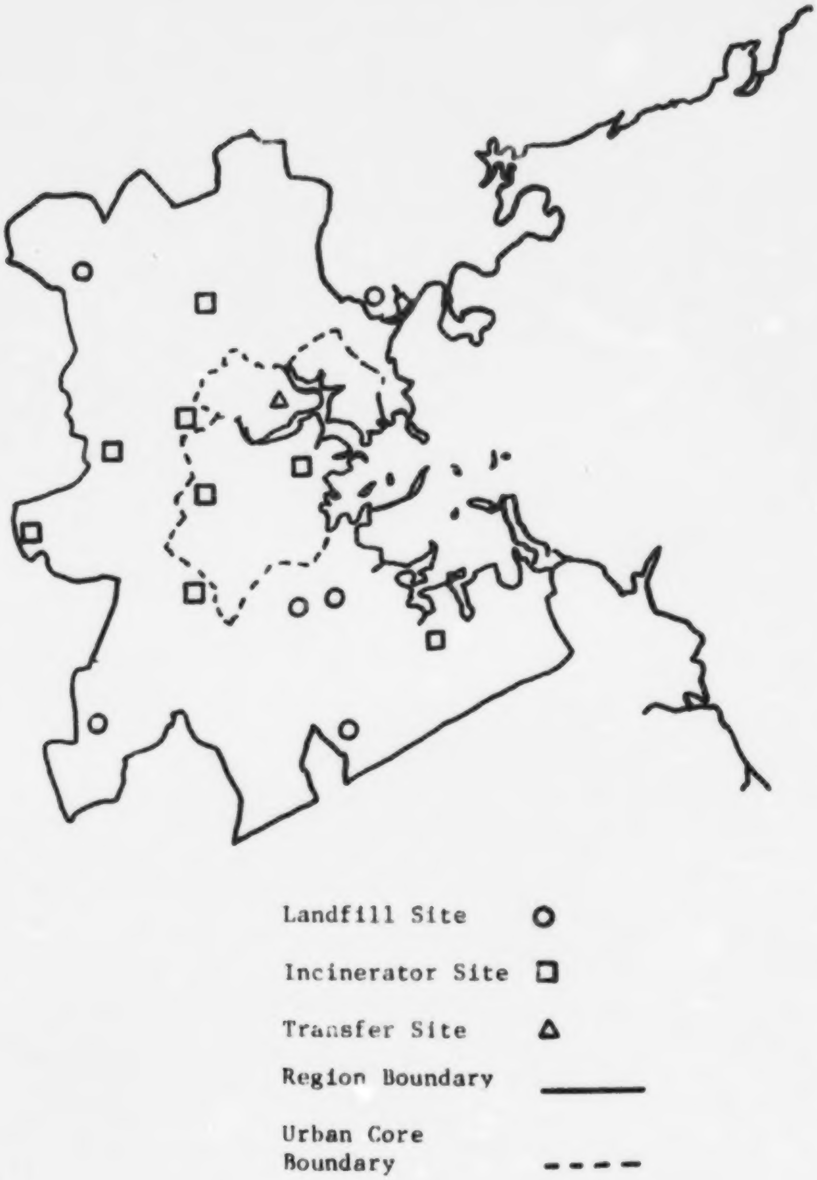
Landfill Site ○
Incinerator Site □
Transfer Site △
Region Boundary ——
Urban Core Boundary - - - -

Figure 9.2: Map of Region Showing Feasible Sites for Facilities Locations

Generating Area	1970-1980	1980-1990	1990-2000
1) Central Boston	1,050	1,210	1,340
2) Cambridge, Somerville, Charlestown	1,300	1,480	1,630
3) Malden, Revere, Chelsea Winthrop, Everett, East Boston	1,790	2,170	2,480
4) Stoneham, Wakefield, Melrose Reading	990	1,230	1,470
5) Woburn, Medford, Winchester	770	1,010	1,170
6) Arlington, Belmont, Watertown	960	1,190	1,300
7) Bedford, Lexington, Burlington	520	710	850
8) Waltham	480	560	620
9) Newton	600	730	830
10) Brighton, Allston, Brookline	470	560	680
11) Dedham, South Western Boston	1,960	2,300	2,520
12) Milton, Quincy	770	970	1,170
13) Walpole, Norwood, Westwood	570	770	1,000
14) Braintree, Weymouth, Hingham	900	1,150	1,510
15) Canton, Stoughton, Randolph Holbrook	650	1,000	1,390
16) Wellesley, Needham	870	1,160	1,300

Table 9.1: Thousands of Tons of Residential SW Generated / 10 Year Period

Generating Area	Boston Incinerator	Cambridge Transfer	Saugus L.F.	Winchester I	Watertown I	Lexington L.F.	Brookline I	Newton I	Wellesley I	Dedham I	Milton L.F.	Quincy, L.F.	Holbrook L.F.	Braintree I	Walpole L.F.
	I	R	S	F	V	L	O	N	W	P	G	Q	M	E	D
1) Centr. Boston B	x	x	x				x	x		x	x	x			
2) Cambridge, Charlestown C Somerville	x	x	x	x	x		x	x							
3) Malden et al. E	x	x	x	x											
4) Stoneham et al. S			x			x									
5) Woburn, et al. R		x	x	x	x	x									
6) Arlington et al.F		x	x	x	x	x	x	x							
7) Bedford, Lexington et al.L					x	x		x							
8) Waltham T				x	x	x		x	x						
9) Newton N					x		x	x	x						
10) Brighton et al.M					x		x	x	x	x					x
11) Dedham et al. D	x						x	x	x	x	x	x			
12) Milton et al. Q	x									x	x	x	x	x	
13) Walpole et al.P											x	x	x		x
14) Braintree et al.Y											x	x	x	x	
15) Canton et al. H										x	x	x	x		
16) Needham et al.	x				x		x	x	x	x					

Table 9.2: System Connectivity Matrix

PROCESSING FACILITY / DISPOSAL FACILITY	Braintree	Watertown	Newton	Brookline	Dedham	Winchester	Wellesley	Quincy	Milton	Holbrook	Walpole	Lexington	Saugus
Braintree (E)	x							x					
Watertown (F)		x										x	
Boston (I)								x		x			x
Newton (N)			x									x	
Brookline (O)				x						x			
Dedham (P)					x				x		x		
Cambridge (R)												x	x
Winchester (V)						x						x	
Wellesley (W)							x						

Table 9.3: Connectivity of Transshipment Network

to ship from a generating area to all facilities. Complete connectivity is possible with this model. However, limited connectivity is advantageous, since it leads to shorter computing time and smaller data requirements. In this study, no generating zone was connected to more than eight disposal sites. Table 9.2 shows the connectivity of the network. An "X" in a particular row and column indicates that the area forming that row is connected with a feasible shipping variable to the facility of that column.

Similarly, Table 9.3 shows the connectivity (or feasible transshipment activities) between treatment facilities and disposal facilities. Again, an "X" indicates that a transshipment is feasible. A number of the incinerators enumerated by this study are located next to special purpose landfills, which process only incinerator residue from the neighboring incinerator. These landfills cannot expand in capacity from their initial starting capacity.

In this study the other treatment and disposal facilities are given zero capacity at the start of the system operation, and have no constraint on capacity expansion. If the system were to be used for actual municipal planning, it would be desirable to include both these terms. (The model formulation earlier in this report outlines the format for including both these terms). However, the purpose of this work was not to propose immediate policy actions for the Boston area and in addition, data on existing capacity and future expansion capability were not available. Cost functions for capacity expansion and facility operation were developed from the literature, as was information on shipment costs and volume reduction.

9.5 Case Study Results

While the terminal solutions obtained in searches for minimum cost solutions may not be globally optimal, they are certainly good solutions approximating optimality. These solutions should therefore be highly useful aids to good system design and worthy of examination.

Computer output indicated that local optima were found for each of the three cost measures, NPV4, NPV8, and NPV12. Two techniques were used to attempt to improve upon initially output solutions. First, the duals of the initial problems were solved. This step was never successful in displacing initial solutions. Second, separable variables were initially set at their lower bounds before solving the problem (in the first solution, separable variables were set at their upper bounds prior to solution). This technique was successful in pointing up local optima in the problem for all three cost measures. In two cases, lower total costs were output when separable variables were initially to ship from a generating area to all facilities. Complete connectivity is possible with this model. However, limited connectivity is advantageous, since it leads to shorter computing time and smaller data requirements. In this study, no generating zone was connected to more than eight disposal sites. Table 9.2 shows the connectivity of the network. An "X" in a particular row and column indicates that the area forming that row is connected with a feasible shipping variable to the facility of that column.

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Table 9.4 shows results of the cost minimization runs with different starting procedures for the three measures of net present value. Careful examination of Table 9.4 gives additional evidence of local optima. When total cost with a 4% interest rate was minimized, $109.46 million dollars was output as the "optimal solution". However, the strategies output minimizing total cost using 8 and 12% interest rates both had values for NPV4 (net present value, assuming 4% interest rate) which were less than $109.46 million, stated to be the optimal value for this variable. Two attempts were made to optimize the three cost measures. Of the six "optimal" solutions output, four were clearly sub-optimal. Improvements over solutions output as optimal were never found to be larger than 4%. However, the improvements exist and this suggests that other better solutions still may exist.

Table 9.5 presents a profile of optimal solutions for the two public policy objectives, and the same information for the best solutions found for the three cost considerations. Information in Table 7 includes a breakdown on capital and operating expenditures by period as well as information of the extent the three types of waste treatment and disposal technologies were utilized. This information is presented for the 5 strategies which best fulfilled the 5 different objectives (EQ, DIST, NPV4, NPV8, and NPV12). Table 9.5 also includes this information for the second best strategies found for the three cost measures so that the reader can observe certain aspects of local optima in this problem.

Perhaps the most noticeable trend in Table 9.5 is the contrast between the three cost minimization strategies and the two public policy objectives. The least cost strategies have fewer sites than do the best public policy stategies, as one would expect. The public policy strategies are more intensive in incineration than are least cost strategies. This is because least cost strategies ship waste to distant landfills rather than use costly incinerators near the site of generation. Public policy goals minimize long waste shipments, and therefore select the incinerators near the generated waste. The differences between the least cost strategies using different interest rates were very slight on an aggregate level. Although the number of facilities tended to increase with interest rates

Separable Variables Initially at Lower Bounds

Objective Function	Total Cost 4% Interest NPV4 $\$x10^6$	Total Cost 8% Interest NPV8 $\$x10^6$	Total Cost 12% Int. NPV12 $\$x10^6$	Waste Shipped over Dist. Lines EQ tons x 10^6	Waste Shipped Dist. ton-miles x 10^6
TOTAL DISCOUNTED COST (4%) INTEREST NPV4	109.46	73.38	54.72	48.8	315.
TOTAL DISCOUNTED COST (8%) NPV8	109.08	72.49	53.62	46.8	328.
TOTAL DISCOUNTED COST (12%) NPV12	109.17	72.51	53.60	42.1	332.

Separable Variables Initially at Upper Bounds

TOTAL DISCOUNTED COST (4%) NPV4	113.63	73.48	52.96	47.3	303.
TOTAL DISCOUNTED COST (8%)-NPV8	114.25	73.32	52.49	46.3	320.
TOTAL DISCOUNTED COST (12%)-NPV12	114.25	73.32	52.49	46.3	320.
TONS OF WASTE SHIPPED ACROSS BOUNDARIES - EQ	173.	125.	100.	23.4	226.
TOTAL TON-MILES OF WASTE SHIPMENTS-DIST	310.	142.		21.9	168.

Table 9.4: Results of Optimization Runs

	Alternative Objectives			
	Total Cost† 4% Interest Lower Bound Start-Up	Total Cost† 8% Interest Lower Bound Start-Up	Total Cost‡ 12% Interest Lower Bound Start-Up	Tons of Waste Shipped Across Dist.Lines*
SANITARY Landfill				
# of Expan	8	8	8	18
# of Sites	4	4	4	6
Total Expansion** + Processing	51.041	51.27	51.27	38.67
INCINERATION				
# of Expan.	2	4	4	15
# of Sites	2	2	2	8
Expansion total**	.88	.88	.88	11.39
Processing total**	2.5	2.2	2.2	21.49
TRANSFER STATION				
# of Expan	1	1	1	1
Expansion total**	2.12	1.16	1.16	.56
Processing total**	4.24	2.32	2.32	.82
OPERATING EXPENSES**				
1970-1979	$38.3	$38.49	38.49	49.01
1980-1989	56.6	57.77	57.76	68.72
1990-1999	64.4	67.56	67.70	79.49
CAPITAL EXPENSES***				
1970-1979	10.8	9.52	9.41	42.84
1980-1989	11.5	10.77	11.01	18.25
1990-1999	1.39	1.83	1.83	14.68

* Optimal Solution
† Best Local Optimum Found
‡ Second Best Local Optimum Found
**In Millions of Tons of Waste
***In Millions of Dollars

Table 9.5: Profiles of Good/Optimal Strategies with Objectives

	Alternative Objectives			
	Total Cost,‡ 4% Interest Upper Bound Start-Up	Total Cost‡ 8% Interest Upper Bound Start-Up	Total Cost† 12% Interest Upper Bound Start-Up	Ton Miles of Waste Shipments *
SANITARY LANDFILL				
No. of Expansions	14	14	14	11
No. if Sites	6	6	6	6
Total Expansion**	51.10	50.23	50.23	30.69
INCINERATION				
No. of Expansions	5	5	5	19
No. of Sites	3	3	3	8
Total Expansion**	.975	.875	.875	11.20
Total Processing**	2.19	2.205	2.205	27.46
TRANSFER				
No. of Expansion	1	1	1	2
Total Expansion**	1.16	1.16	1.16	2.69
Total Processing**	2.32	2.23	2.23	4.62
OPERATING EXPENSES***				
1970-1979	36.92	35.80	35.80	41.75
1980-1989	60.87	64.67	64.67	68.68
1990-1999	71.33	72.48	72.48	72.85
CAPITAL EXPENSES***				
1970-1979	7.67	7.54	7.54	40.18
1980-1989	12.58	10.85	10.85	26.88
1990-1999	8.95	9.39	9.39	7.75

* Optimal Solution
† Best Local Optimum Found
‡ Second Best Local Optimum
**In Millions of Tons of Waste
***In Millions of Dollars

Table 9.5(continued): Table of Good/Optimal Strategies for all three technologies, the total installed capacity and total processing by technology remained very close for all interest rates investigated. Table 9.5 illustrates that the nature of the least cost strategy is fairly insensitive to interest rates. The three technologies remain in approximately the same ratio for all three interest rates. There was a slight trend towards higher operating expenses and lower capital expenses for the higher interest rates, but this trend was not related to any shift in technology mix.

The least cost strategies for the case study were very intensive in the landfill mode of solid waste treatment. This is not wholely realistic in the sample study due to a number of assumptions made in formulating and carrying out the model.

First, all sites could expand indefinitely in the sample case. This is unrealistic since many of the landfill sites studies have very limited potential expansion capacity. This unrealistic element of the case study was purposely included. The solid waste disposal problem in the Boston area is acute, and landfill capacity is very small. Realistic capacity expansion constraints would have determined the solution, and little insight could be gained outside the specific case of Boston. In this model, economic consideration determined the nature of the final solution. This may be a source of greater insight to the reader.

Second, no capacity was initially assumed to be in existence at any site. All facility expansion takes place inside the model. This was so designed in order to observe what the system should be like, not what the system is like now (and what it will be like in the future given previous decision). As a result, a number of sites with existing incinerators capacity were not used.

Finally, the model does not place any value on capacity which will exist after the 30 year planning period is over. Unless the model is so constrained by the planner, no landfill capacity will remain at the end of the planning horizon. As a result of these three factors, least cost strategies are biased towards landfill operations. Nonetheless, the case study points up the attractiveness of landfill when that option is available. In the case study incineration is the least cost alternative when no landfill is nearby. Transfer station operation was utilized in all least cost strategies on a modest scale.

	1970 - 80	1980 - 90	1990 - 2000
Zones Near Landfills			
Malden, Revere, Chelsea, East Boston, Winthrop, Everett	1.42	.78	.37
Stoneham, Wakefield, Reading, Melrose	1.63	.91	.43
Quincy, Milton	1.19	.63	.31
Walpole, Westwood, Norwood	1.83	.78	.38
Lexington, Burlington, Bedford	1.31	.69	.33
Canton, Stoughton, Randolph, Holbrook	1.62	.91	.38
Zones Near Incinerators			
Central Boston	1.50	.79	.43
Woburn, Medford, Winchester	1.87	1.03	.49
Arlington, Belmont, Watertown	1.70	1.46	.70
Brighton, Allston, Brookline	1.17	1.11	.53
Newton	5.10	2.30	1.32
Wellesley, Needham	.44	2.61	1.37
Dedham, Southwest Boston	1.50	.83	.44
Braintree, Weymouth, Hingham	1.81	.83	.42
Other Zones			
Cambridge, Somerville, Charleston	1.92	1.09	.52
Waltham	1.77	.98	.47

*units are dollars per ton of waste

Table 9.6: Shadow Price on Load Constraint for Each Time Period*

	1970 - 80	1980 - 90	1990 - 2000
Incinerators			
Boston	1.89 - 11.14	2.03	.12 - .21
Braintree	4.13	1.55 - 5.24	.26
Winchester	2.84	1.05	.50
Dedham	4.40	1.18 - 3.85	.89 - 1.66
Watertown	1.89	1.61	.88
Wellesley	4.40	.60 - 3.84	.94 - 1.58
Brookline	1.69 - 7.79	1.75	.94
Newton	3.46	1.45	.92
Landfills			
Holbrook	.078	.078	.012
Walpole	4.23	.027	.012
Quincy	.078	.078	.012
Lexington	.060	.027	.012
Milton	.17	.078	.078
Saugus	.17	.078	.036
Transfer Stations			
Cambridge	1.47	.57	.40

*units are dollars per ton of waste

Table 9.7: Shadow Price on Capacity Constraints for Each Time Period

Possibly because of the large number of sites available for flows and because cost functions were uniform for all sites of the same technology, optimal strategies have a large number of basic variables at zero value. This means that the nature of the least cost solution can change in a number of ways without changing the total cost of the system. This is true for shipping variables as well as processing variables for competing technologies.

Sensitivity Analysis - Insights into the nature of the problem can be gained by looking at shadow prices and opportunity costs of the least cost solution. These values reveal the marginal cost for loosening a given constraint by one unit. An opportunity cost is the amount a variable input cost must be changed before the status of the variable in the optimal solution changes. This information is readily available form the mathematical programming process, and is very useful for analysis.

For example, the shadow price on the constraint requiring that all waste generated in a zone will be treated has an interesting economic interpretation. It represents the marginal haul and disposal cost of generating an additional ton of waste in that zone. As shown in Table 9.6, the shadow prices on this constraint vary widely. Newton, which utilized incinerator waste treatment, had the highest shadow price on this constraint. Lexington and Quincy, which utilized nearby landfills, had relatively low shadow prices for this constraint. Note that shadow prices decline in future years due to cost discounting.

The shadow price on the facility capacity constraint is the marginal cost of increasing capacity by one unit. The use of shadow price analysis is especially helpful in this study, since concave cost functions were used. Marginal capacity expansion costs tend to be high for incinerators and transfer stations when compared to landfill expansion costs. Sites at high capacity levels have lower shadow prices than sites of the same technology operating at low capacity levels. Table 9.7 shows these shadow prices for all sites. Sites are grouped by technology and listed in order of increasing operating levels summed over all three periods. Where two costs are listed for one entry, the first represents the system cost of reducing capacity at a site by one unit, the second is the cost of increasing capacity at that site by one unit. Capacity is in units of tons of waste per 10 year period.

Table 9.8 shows the marginal processing cost of each facility. Table 9.8 is in the same format as Table 9.7, and in the same units. Note that the facilities are again listed in order of increasing operating levels. The marginal costs reflect economies of scale, falling as facility utilization rises.

Facility Site	1970 - 80	1980 - 90	1990 - 2000
Incinerators			
Boston	12.29	.21	2.68
Braintree	12.52	5.76	.26 - .57
Winchester	12.49	.35 - .26	.50 - .26
Dedham	12.38	5.77	2.68
Watertown	2.44	.55	.25
Wellesley	2.28	1.93	1.10
Brookline	4.49	.54	.26
Newton	1.18	.55	.25
Landfills			
Holbrook	4.30	.54	.17
Walpole	.60 - 2.99	.37	.17
Quincy	1.01	.28	.17
Lexington	.80	.37	.17
Milton	.60	.28	.13
Saugus	.60	.28	.13
Transfer Stations			
Cambridge	1.06 - 1.52	1.65	.77

*units are dollars per ton of waste

Table 9.8: Shadow Price on Processing Constraints for Each Time Period

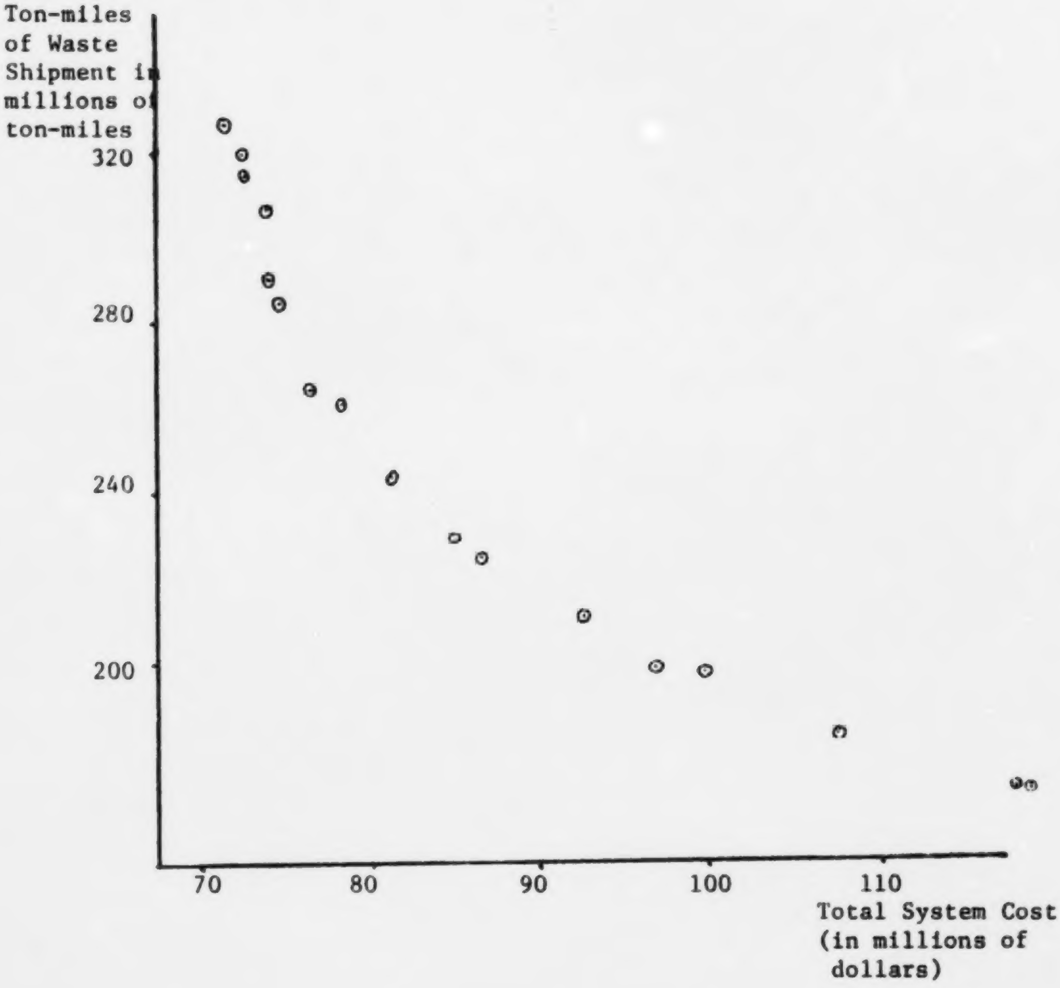

Figure 9.3 Trade-Off Curve
System Cost Versus System Equity

Tradeoff Analysis - The profiles of the least cost strategies are very different from those of the strategies which best fulfill the public policy goals. Since both economic and political goals will be important for most public systems, it would be desirable to examine strategies which are appealing under both criteria. It is possible using mathematical programming to move from one extreme to the other by a parametric sweeping procedure.

To illustrate this procedure, consider the two competing objectives, DIST and NPV8. The procedure for moving from the optimal strategy for DIST to the best known strategy for NPV8 is fairly straight forward. Given that D^* is the optimal level of DIST and that N^* is the optimal level for NPV8, one may choose NPV8 as the objective and constrains DIST to be less than or equal to D^*. This constraint is parametrically slackened by increasing the permissable value for DIST, and with each slackening a new optimum of NPV8 is found. The procedure terminates when the DIST constraint is no longer binding and NPV8 can feasibly be lowered to N^*, its optimal level.

This procedure was performed for this problem, and the results trace out the curve shown in Figure 9.3. The vertical axis is net present cost of the solid waste disposal system, and the horizontal axis is ton-miles of shipments of solid waste. Note that the curve is not quite smooth, and that there are a number of small bumps in the curve. These small irregularities in the generally smooth curve result from the separable cost functions used.

The tradeoff curve for this problem changes rather gradually from cost oriented strategies to politically oriented strategies. There is no sharp kink in the tradeoff curve.

The tradeoff curve can be used in a number of ways. It may simply be derived by the analyst and presented to the decision maker as a locus of dominant strategies, given the two alternative objective functions. The decision maker may then select his most desired operating point on the tradeoff curve.

Alternatively, the analyst may determine the "utility functions" of the decision maker (using the techniques of decision analysis (109))and the utility functions in conjunction with the tradeoff curve in recommending a specific strategy as the most desirable alternative.

On the same axes as used for the tradeoff curve, the analyst can plot the utility functions he has derived from the decision makers. As proved in Lancaster (70), the most desirable operating point occurs where the tradeoff curve lies tangent to the utility curve. Note that for tradeoff curves with sharp bends or kinks, the most desirable point of operation will remain essentially unchanged for a wide range of utility functions.

The generation of tradeoff curves is a very good way of treating a series of alternative objectives. The process enables the decision maker to see quickly the range and nature of alternatives open to him, and helps him to put competing alternatives in perspective. Finally, the tradeoff curve gives the decision maker a visual display of how much of one objective must be given up in order to gain improvements in a second objective.

9.6 Extensions and Refinements

The model presented here can be extended in a number of ways to treat different problems which might arise in planning a solid waste management system.

First, if the local government owns a site of land but is not certain what type of solid waste disposal or treatment technology should be located on that site (if any), this model can treat the situation. Shipment, transshipment, capacity and processing variables and constraints should all be established for the competing technologies. In addition, a constraint on site availability should be added to insure that the site will be sufficient for the planned capacities:

$$\sum_t \sum_G \beta_G \, Y^G_{it} \leq H_i \qquad \text{for all appropriate } i.$$

where Y^G_{it} = capacity of technology G added at site i in year t

β_G = site area required for a unit of capacity of technology G

H_i = total area of site i

Another issue which may be important in the design of a regional solid waste treatment system is seasonal fluctuation in waste loads. If seasonal peaks and troughs occur at different times in different parts of the study area, it may be possible to use different shipping patterns at different times to limit the seasonal variation faced by individual facilities. This cooperative use facilities will reduce excess capacity requirements needed to handle seasonal variation. Although considerable added computational and data collection costs may be incurred, seasonal waste load variation can be treated in this model by setting up waste loads, shipping variables and capacity constraints for each season of interest.

If seasonal peaks and troughs occur at the same times throughout the study area, seasonal variation can be treated by multiplying average waste loads by a rationally determined "safety factor" (59).

A final extension is presented to evaluate sensitivity of solutions to waste load projections. Solid waste management requires two types of decisions: major facility location and capacity sizing decisions (which will have long term system impacts) and day to day shipping and operating impacts. Due to long lead time requirements capacity expansion decisions must be made using uncertain waste loads. A number of alternative waste load projections may be reasonable under different optimal capacity expansion strategies. It is possible to choose among the competing strategies using subjective probability assessments and the techniques of decision analysis (109).

As an example, consider three possible waste load projections, A, B, and C, for the region under consideration. Also, assume that probabilities p_a, P_B, p_c can be derived for the three waste patterns, with these probabilities representing the decision makers best estimate of the probable likelihood that the given pattern of waste loads will be correct. The subjective probability assessments must sum to one.

For each load pattern, find the optimal solid waste management strategy, S_A, S_B, S_C, and its cost, $C(A|A)$, $C(B|B)$, and $C(C|C)$. Next, determine the consequences of incorrectly estimating waste loads. To do this, constrain capacity expansion levels equal to those in S_A. Next examine system performance under waste loads B and C given facility capacities constrained to levels in S_A. Label these performances $C(A|B)$ and $C(A|C)$. Next, constrain capacity decisions to those found in S_B and find $C(B|A)$ and $C(B|C)$ by optimizing performance for waste loads A and C. Repeat for S_C, finding $C(C|A)$ and $C(C|B)$. Note that $C(i|i)$ should always be more desirable than $C(j|i)$, $j \neq i$, since the latter will have excess capacity and/or high transport costs.

Competing strategies may be evaluated using

$$C^*_j = \sum_{i=a,B,c} P_i \quad C(j|i)$$

where C^*_j = expected performance of acility expansion decisions j

P_i = subjective probability that waste load set i will become true

$C_{(j|i)}$ = performance of facility expansion decisions j given that waste load set i is true.

A thorough framework has been established to select among the strategies given the decision makers reactions to risk and uncertainty. However, in many cases, it may be desirable to select the capacity expansion pattern j with the lowest C^*_j.

When this analysis is performed, it may be useful to model a "safety valve" site into the capacity structure of the problem. Such a site should reflect costs of disposing of waste when waste loads exceed installed capacity. These increased costs may include overtime costs for 24 hour facility operations, haul to facilities outside the study area, and other operations which would not normally be undertaken. A safety valve site will keep the system feasible when future waste loads have been underestimated, and will also reflect the cost of extraordinary operating procedures.

9.7 Conclusions

The regionalization problem is an important one. While some relief may be in sight (through improved technology), the problem of placing processing and disposal facilities will continue to be important. It is clearly possible that solid waste may achieve a new image, with efficient and sanitary landfills, processing plants which reclaim materials from waste, and an increased understanding of the problems by the public. States will continue to expand their roles, and "meddle" in local systems, removing the problem a level; regional governments may expand. However, the least likelihood of a miracle will be in those areas which need one most, simply because of denser land use and stronger local constraints. Masschusetts, for example, is totally incorporated with strong town governments and very weak counties. Intergovernmental cooperations is difficult, at best. The probability of finding an answer which is both efficient and equitable, as well as acceptable, may be low. The model described above can be viewed as a first attempt to look at questions which are important to the decision makers who must plan and implement regional systems, and to go beyond simple economic efficiency to look at some of the issues which impinge [illegible] political feasibility.

IMPLICATIONS FOR ANALYTIC MODELLING IN SOLID WASTE COLLECTION

This report has described the state of the art and developed new techniques for analytic modelling of solid waste collection systems in a manner which will enable both managers and future researchers to best use the present methodology in improving the operation of waste collection systems. Solid waste is a major problem in urban areas, and is an important service for municipalities to provide to residents. The application of system analytic techniques has been limited by the available methodology; case studies based on techniques rather than on the real problems abound. It seems to us that the potential for valuable decision aids in analytic models should soon yield important results at some reasonable expense. Mathematical techniques have been important in engineering design of physical systems throughout history, and have become important management aids in the past few decades. There are, though, several problems in the use of analytic models in solid waste systems. Foremost is cost: most of the present models are too expensive for use in all but the most affluent systems, even though the cost savings provided by them can be great, solid waste management systems have little "risk capital" so that managers tend to be very careful and risk adverse, except in crisis situations.

Marketing of the techniques is being performed by a few consulting firms and many university researchers: these are not groups with significant influence in solid waste systems. In fact, there is a basic dichotomy between the goals of researchers and managers, which often leads to both sides being dissatisfied. Managers tend to require answers quickly, and to expect the researchers to provide something useful, a reasonable set of goals. Researchers, on the other hand, wish to study the problems sufficiently so that they can provide optimal solutions which have been carefully checked, and this can take time. The result is often that the managers feel that nothing is being accomplished because of the long start-up times and the researchers feel that they do not have time to do a decent job because of the need for immediate answers.

Our research has been based on a few simple propositions. We feel that there is a potential for significant change in local collection systems, and that analytic models can be used at fairly low cost to aid in the engineering design and operation of such systems. It is important to predict the consequences of a proposed system, going beyond simple cost analysis to look at environmental impacts and other secondary effects. It is vital to be able to look at the tradeoffs between direct costs and these other effects in the design stage, so that the system choice is done with as much data as possible. Models can help in understanding complex systems such as solid waste collection. It is a very easy practice to construct models which are rooted in the ideas of the researcher. However, such models often fail since they address problems which are not real. The better a model is identified with a particular issue, the greater the probability of significant results. Models should aid decision-makers by serving to identify complex issues in the decision-making process. to look at secondary effects of decisions, and to estimate the magnitudes of the tradeoffs between different objectives of the decision-maker.

Models can also be used as pure design tools. In some situations the simple mathematics and bookkeeping involved in design can be overwhelming, and models can be used here to develop better (or at least, less costly) designs that could be done by hand. Here models can aid the decision-maker by improving design methods or serving as an aid enhancing understanding of the system. Both uses for analytic models are developed in our research. The routing algorithm serves as a pure design aid, a method for guiding trucks around a street network and identifying districts for daily collection. The waste generation work, while important in the routing methodology, aids the manager in understanding the operation of the system and the context in which it operates. The regional processing, haul, and disposal model explicitly identifies tradeoffs between system efficiency and local impacts of waste handling, and develops estimates of the tradeoffs involved. The basic breakdown model looks at the effects of dispatching policies on overloads and vehicle breakdowns, and suggests the costs and benefits of different types of designs in daily operations policies. The node routing model could be used to develop the benefits from changing pickup days for various users, in terms of collection costs. All models must be aids to management as either design tools or as methods for assisting the manager in understanding the operation of the system and the costs and benefits of changes.

Other researchers have developed models for the same purposes. In some cases the result has been more to aid the researcher than the manager; some have become valuable tools and been successfully applied. In general, a few important points emerge for consideration. If possible, the problem should be identified first, not the analysis tool. The methodology should be based on the problem, and on the resource constraints for its application: highly computerized "optimal" routing methods, for example, may be unusable even if they are interesting research topics. Our present system may itself be overly dependent on the computer, even though the design was intended to minimize resource requirements. If implementation ensues, this must involve a continuing dialogue between the research staff and the system manager. Ignoring actual operations only loses understanding of the way the system works in practice.

The decision classifications discussed in the opening chapter have been covered fairly extensively in the literature, both through this project and others. Still, there are a number of areas available for research, and many areas where actual applications are lacking. These are discussed in the body of this report.

As discussed in Chapter 2, there are a large number of organizations involved in solid waste operations, and many other peripheral agencies and consulting firms. Most solid waste collection agencies are organized more towards service than towards cost minimization, however, so implementation may be slow. The analytical techniques assist either in systematic redesign of collection systems, or in improving the efficiency of operations. A system not tightly constrained by cost and operating on the basis of continuing the status quo will not require analytic methods. However, a large number of communities have costs rising without limit and disposal alternatives limited or nonexistent, (especially if environmental standards are to be achieved). These communities, in crisis as well as the more cost-conscious private firms, form the "market" for analytic techniques. Here innovations are likely to be accepted and a significant impact made on the decision process or the operations policies. Obviously, the solid waste system must meet exogeneous constraints. A change from three-man to one-man crews, for example, may be infeasible since jobs for the displaced workers might not be available. Many residents would prefer their present collection system to one which might be objectively "better", at least in the short term. Finally, many managers appear to perform as budget maximizers, and methods which cut a department's budget may not be accepted.

Innovations like analytic methods diffuse slowly through the solid waste system. It is not to be expected that the simple existence of a routing algorithm, for example, will lead to its immediate adoption. The hypothesis that analytic models can be valuable in solid waste systems is difficult to test except through field trials. An alternative is to develop methods quickly and easily applicable for system managers and also their staff. A combination of implementation programs and further research into usable methods should be continued so that both efficiency and understanding of solid waste collection systems can be improved.

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a node. If a node is reached where all streets have been collected, it then follows the shortest path to an open street. While this procedure is simple and easy to understand and program, it is myopic and may lead to horrendous solutions. To understand why, it is necessary to introduce the concept of an "Euler tour". An Euler tour is a route which covers all the arcs of a graph without repeating any arcs. Euler proved that such a route is possible only if there are zero or two odd nodes. Even, if an Euler tour exists though, the Bodner,Cassell and Andros algorithm will not necessarily find it. (see Figure 6.10). On a more complex network, where the problem requires the optimal pairing of odd nodes, the myopic choice of the closest available uncovered arc will lead to even worse solutions. The algorithm, though, is in many ways the state of the art in current solid waste routing practice. This suggests the need for efficient and rational routing methods.

There is an easy visual method for drawing Euler tours in simple graphs: the "isthmus avoiding" algorithm. Start at any point in the network, and cover the edges in any order, taking care only to not divide the set of unused edges into two disjoint groups. While difficult to program since it is a pattern recognition problem, this method is very simple to use manually. Edmonds and Johnson (35) give superior algorithms for computer implementation. Computerized algorithms do not recognize the large number of alternate Euler tours available: manual analysis allows choices to be made to meet secondary objectives, such as minimizing U-turns, travelling one-way streets in the correct direction, and avoiding congested intersections. If it is possible to reduce a given street network to a graph with zero or two odd nodes, the problem is easily soluble. If not, then some arcs must be covered more than once. It can be shown that the optimal solution is that which connects pairs of odd nodes in the least cost manner (see, for example, Mei-Ko (93)). This is equivalent to adding a second arc between certain pairs of odd nodes, which makes them all into even nodes and allows an Euler tour on the augmented network. The pairing of the odd nodes which requires the lowest amount of extra travel is optimal.

In Liebling's work (74,75) in Switzerland, this pairing is comparatively easy. Street cleaning requires that both sides of the street be swept separately, so the normal street cleaning network is directed (see figure 6.11). Any odd node had either a surplus of origin nodes or a surplus of destination nodes (see Figure 6.12). Pairing these, though, is a matter of pairing origin nodes with destination nodes at minimum cost, which is just the Hitchcock Transportation Problem and can be solved using any of the available network analysis or linear programming codes.

Shuster and Schur develop techniques for the manual routing of vehicles in simple systems (141); while not primarily concerned with minimizing mileage, they do suggest methods for generating routes with better turn patterns. For example, clockwise loops around